Arnold Schwarzenegger
Governor

PUBLIC HEALTH BENEFITS OF END-USE ELECTRICAL ENERGY EFFICIENCY IN CALIFORNIA: AN EXPLORATORY STUDY

PIER FINAL PROJECT REPORT

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Prepared By:
Lawrence Berkeley National Laboratory
Dr. Thomas E. McKone, Principal Investigator
Dr. Agnes B. Lobscheid, Principal Research Associate
Berkeley, California 94720
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Prepared For:
Public Interest Energy Research (PIER) Program
California Energy Commission

Gina Barkalow
Project Manager

Beth Chambers
Contract Manager

Kelly Birkinshaw
Program Area Lead
Energy-Related Environmental Research

Laurie ten Hope
Office Manager
Energy Systems Research

Martha Krebs
Deputy Director
ENERGY RESEARCH & DEVELOPMENT DIVISION

B.B. Blevins
Executive Director

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Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Energy Commission), conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

The PIER Program strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy Innovations Small Grants
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

Public Health Benefits of End-Use Electrical Energy Efficiency in California: An Exploratory Study is the final report for the Public Health Benefits of End-Use Electrical Energy Efficiency in California project (contract number 500-02-004) conducted by Lawrence Berkeley National Laboratory. The information from this project contributes to PIER's Energy-Related Environmental Research Program.

For more information about the PIER Program, please visit the Energy Commission's website at www.energy.ca.gov/pier or contact the Energy Commission at 916-654-5164.

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Abstract

This exploratory study applies a life-cycle impact assessment framework to calculate the public health benefits of increasing the end-use efficiency of electric energy. Installation of fiberglass attic insulation in electricity-heated homes throughout California was used as a case study. Disease burden from nitrogen oxides (NO_x), sulfur dioxide (SO_2), fine particulate matter (PM2.5), benzo(a)pyrene, benzene, and naphthalene was assessed. Exposure was characterized separately for rural and urban environments using the CalTOX model. CalTOX provides urban and rural emissions-to-intake factors, expressed as an individual intake fraction (*iFi*). The typical *iFi* from power plant emissions was on the order of 10^{-13} (g intake per g emitted) in urban and rural regions. The cumulative (rural and urban) product of emissions, population, and *iFi* was combined with toxic effects factors to determine human damage factors, which were expressed as disability-adjusted life years (DALYs) per kg pollutant emitted. Upgrading residential insulation to levels recommended by the U.S. Department of Energy eliminates—over the assumed 50-year lifetime of the insulation—approximately 1000 DALYs from power plant emissions per megatonne (Mt) of insulation installed, mostly from the elimination of PM2.5. In comparison, the estimated disease burden from the manufacture of this insulation is roughly four orders of magnitude lower than that avoided.

Keywords: End-use energy efficiency, health impacts, disease burden, fiberglass insulation, DALY, TRACI, CalTOX

Executive Summary

Introduction

Fossil-fueled power plants emit numerous airborne pollutants that have varying effects upon public health and the environment. A 2004 Externalities of Energy (ExternE) study by the European Commission reports that the value of public and occupational health impacts attributable to energy use is on the order of $25,000 per gigawatt-hour (GWh). Efforts to curb these emissions typically focus on control at the power plant. However, end-use energy efficiency—using more-efficient electrical devices on the consumer end—is another way to reduce the emissions associated with power generation. For example, a more-efficient refrigerator requires less electricity to provide the same level of cooling, thus reducing the need for power generation and its concomitant emissions.

Over recent decades, there has been extensive research to assess and compare the health risks of electrical energy production but little effort to use these studies to determine the benefits of increasing end-use efficiency. Increasing end-use efficiency would provide public health benefits by reducing emissions from fossil fuel combustion at power plants. But efficiency gains have cost implications and their own set of potential health risks. Consumers, businesses, and policy makers require better information on the relative health benefits of using energy more efficiently. Research needs to move beyond a qualitative understanding of this issue by specifically quantifying the changes in both emissions and source-to-dose relationships for energy-related pollutants in a large and well-characterized market such as California.

Purpose

This exploratory project applied standard methods of life-cycle impact assessment (LCIA) to the problem of quantifying both the public health hazards avoided and those substituted by increasing the end-use efficiency of electricity use in California. As a case study, the project quantified the changes in power plant emissions and associated disease burden resulting from the installation of fiberglass attic insulation in the nearly 3 million electricity-heated homes throughout California. These estimates were compared with the disease burden from the manufacture of fiberglass insulation to determine the net health impact of installing the attic insulation.

Objectives

This report describes a definition study rather than a comprehensive life-cycle-assessment. In this context, the objectives of this project were to:

- Provide a roadmap to organize a health benefits study for energy efficiency.
- Demonstrate the use of life-cycle impact assessment tools to fill in this roadmap.
- Provide an informative case study to illustrate how one can construct and evaluate a health benefits study for energy-efficiency improvements in California.

To meet these objectives, the research team employed standard LCIA tools that have been developed for evaluating and allocating the health and environmental impacts of energy technologies. Databases from the U.S. Environmental Protection Agency (EPA) and the California Energy Commission were used for determining emissions locations and magnitude. Exposure assessments were based on the CalTOX regional mass-balance model for criteria pollutants and hazardous air pollutants.

Outcomes

The study focused on nitrogen oxides (NO_x), sulfur dioxide (SO_2), fine particulate matter (PM2.5), benzo(a)pyrene (BaP), benzene, and naphthalene emissions from California power plants. Exposure was characterized separately for rural and urban environments using UC Berkeley's CalTOX model, a multimedia fate and exposure model used for exposure assessment in the U.S. Environmental Protection Agency's Tool for the Reduction and Assessment of Chemicals and other environmental Impacts (TRACI) (Bare et al. 2002). The output from CalTOX provided separate urban and rural emissions-to-intake factors, which were expressed as an individual intake fraction (*iFi*). The cumulative (rural and urban) product of emissions, population, and *iFi* was combined with toxic effects factors to determine human damage factors (HDFs). HDFs were expressed in disability-adjusted life years (DALYs) per kilogram of pollutant emitted.

Typical individual intake fractions (*iFi*) from power plant emissions were found to be on the order of 10^{-13} (10^{-15} for BaP) in urban and rural regions. HDFs were dominated by premature mortality due to inhalation of PM2.5. HDFs for PM2.5 were roughly two orders of magnitude greater than inhalation exposure HDFs for the other five chemicals. Upgrading existing residential insulation to levels recommended by the U.S. Department of Energy (DOE) was found to eliminate—over the estimated 50-year lifetime of the insulation—approximately 1000 DALYs from power plant emissions per million metric tonnes (Mt) of insulation installed. In comparison, the manufacture of this insulation results in an estimated DALY per Mt that is roughly four orders of magnitude less than the DALYs avoided. This translates to a net avoidance of approximately 110 premature deaths over the 50-year lifetime of the insulation—mostly due to a reduction in PM2.5 emissions.

Conclusions

This study was successful in organizing the roadmap, data, and computational tools needed to assess both disease burden and health benefits from changes in electricity consumption in California. The framing of this problem produced a repository of important information that will be useful for future comparative studies.

The researchers demonstrated the use of a standard LCIA approach (TRACI-CalTOX) to determine how atmospheric emissions from power plants distribute in the environment and what populations are impacted by the associated cancer and non-cancer disease burdens. A case study calculated the disease burdens averted due to the installation of approximately 1.1 million metric tons (Mt) of additional fiberglass attic insulation in California residences to reach DOE-recommended levels. Based on a 50-year assumed lifetime of the installed insulation, the avoided disease burden is approximately 10^3 DALYs (or 115 averted deaths) from power plant emissions per Mt of insulation installed, mostly from the elimination of PM2.5 and, to a lesser extent, NO_x, emissions. This health benefit far outweighs—by four orders of magnitude—the disease burden associated with the manufacture of this additional insulation.

Recommendations

The demonstrated utility of the LCIA framework for this study supports evaluation of this approach for other comparative health benefits studies. For example, this framework could also be used to assess the health benefits of fuel efficiency in the transportation sector.

The successful application of the TRACI-CalTOX LCIA approach reveals the value of exploring how this system could be applied to life-cycle studies of other energy production and energy efficiency technologies. Because existing LCIA methods have been developed for generic applications in life-cycle assessment, there is a need to expand, test, and support use of LCIA methods for comparative energy assessments in California.

Estimates of PM2.5 emissions and disease burden resulting from the manufacture of fiberglass insulation are so limited by uncertainty that a formal uncertainty analysis is needed to confirm conclusions about net health benefits of fiberglass insulation. Also, there is a need to consider a broader range of pollutant emissions, such as secondary aerosols, to assure that PM2.5 is indeed the dominant contributor to disease burden.

Benefits to California

By including energy efficiency in comparative assessments for the current mix of energy technologies, the results and, in particular, the methods and data of this study, provide benefits to energy planning for California. Among the key benefits are:

- A potential tool for more informed decision making, based on the ability to aggregate and systematically evaluate information on potential environmental implications of alternative energy systems in the context of energy efficiency choices.
- An example of how this tool could be used to make decisions about improvement options for environmental quality by identifying optimal areas for reducing emissions/effluents and so forth on the basis of a comparative assessment of population disease burden associated with alternative supply and end-use management options.
- An example of a more systematic approach for consideration of potential environmental and human health effects within the broader decision-making process.

1.0 Introduction

1.1. Background and Overview

Over recent decades, there has been extensive research to assess and compare the health risks of electrical energy production, but little effort to use these studies to determine the benefits of increasing end-use efficiency. No prior research has confronted the more specific question of the net public health benefits—both premature mortality and disability, based on spatial resolution of urban and rural region-specific emissions—from increasing end-use efficiency in California or the nation. The goal of this exploratory project is to construct and evaluate a framework to calculate regional-specific exposure reductions and the corresponding health benefits of increasing the end-use efficiency of electric energy in California.

Recent studies on the impacts of electricity production include the United Nations International Atomic Energy Agency (IAEA) study on the comparative health and environmental impacts of electricity generation systems (IAEA 1999) and the ExternE project (ExternE 2004). These studies take a fuel-cycle approach, where impacts from fuel acquisition through waste disposal are estimated. The results provide useful insights and help promote further studies of impacts for many more technologies, sites, and regions. However, because these comparative studies have to date excluded energy efficiency in the mix of technologies considered, there remains an important gap in the information available to policy makers for making well-informed decisions on energy choices for California. The focus of this study is emissions, environmental fate, human exposure, and indicators of public health impact that apply to end-use efficiency.

This report addresses the problem of quantifying both public health hazards and health risks avoided and those substituted by increasing end-use efficiency in California. The generation, transmission, and use of electricity have all been demonstrated to have adverse impacts on the environment (ORNL 1992; Ontario Hydro 1993; Dincer 1999; IAEA 1999; ExternE 2004; Bare et al. 2002). Increasing the efficiency of electricity use provides public health benefits by reducing these environmental impacts (principally, by reducing emissions from fossil fuel combustion at the power plant). But end-use efficiency gains have cost implications and their own set of potential health risks—such as emissions created during the manufacture of the energy-efficient products. There is clearly a need for consumers, businesses, and policy makers to have better information on the relative health benefits of using energy more efficiently.

Often end-use reduction technologies are evaluated only in terms of their relative cost savings based on the financial cost of equipment purchase and deployment. Environmental health scientists recognize that there are clear health benefits to reduced energy production. There is a need for research to move beyond a qualitative understanding of this issue by specifically quantifying the changes in both emissions and source-to-dose relationships for energy-related pollutants in a large and well-characterized market such as California.

The research goal of this project is to quantify the energy-related environmental and public health benefits of end-use efficiency using comparative health assessments. These assessments are designed to capture differences in impact among alternative production and efficiency technologies. By including energy efficiency in the mix of technologies encompassed in comparative assessments, the results of this study will contribute to more informed decision making. This exploratory study therefore provides more complete information on potential environmental and health implications of alternative energy systems in the context of energy efficiency choices.

1.2. Project Objectives

Fuel cycles for energy production technologies can be characterized in terms of an upstream phase (resource extraction, component manufacture, fuel extraction, etc.), a production phase (the actual electricity production facility), and a waste-management phase. Similarly, technologies for the efficient end use of electricity have upstream, use, and disposal phases. To quantify cumulative health impacts for all these stages requires a life-cycle approach. Given the limited timeframe and budget for exploratory grants, this report describes a definition study rather than a comprehensive life-cycle assessment. In this context, the objectives of this project were to:

- Provide a roadmap to organize a health benefits study for energy efficiency. This has not been done before for California; thus it was necessary to create a roadmap within which it was possible to track, based on available data, and with sufficient transparency and a reasonable amount of assumptions, the emissions from power plants and reduction in emissions from a specific energy-efficient end-use technology.
- Demonstrate the use of life-cycle impact assessment tools such as the U.S. Environmental Protection Agency's TRACI-CalTOX system (Bare et al. 2002) to fill in this roadmap.
- Provide an informative case study to illustrate how one can construct and evaluate a health benefits study for energy-efficiency improvements in California.

To meet these project objectives, the research team employed standard life-cycle impact assessment (LCIA) methods that have been developed for evaluating and allocating the health and environmental impacts of energy technologies (Guinée and Heijungs 1993; Guinée et al. 1996; Hertwich et al. 1998 and 2001; Hoffstetter 1998; IAEA 1999; Huijbregts et al. 2000; Bare et al. 2002; ExternE 2004). LCIA is a subset of life-cycle analysis (LCA) that explicitly and quantitatively looks at the impacts of a given technology (environmental, health, economic, etc.). In this report, health impacts from power plant emissions and the manufacture of insulation were examined. These methods provide a quantitative assessment of the contribution of life-cycle inventory data to environmental impacts, including human health effects. As shown by Figure 1, impact assessment is a key phase in any LCA. Because this LCIA study primarily focuses on potential health benefits, it does not have an economic or epidemiological focus.

The traditional approach to examining impacts typically focuses on single facilities (e.g., a power plant) and site-specific assessments. In contrast, LCIA takes a broader approach and looks at cumulative impacts over a large region (e.g., urban and rural regions) and over a longer period of time. LCIA is more transparent and allows the user to explore different alternatives for achieving the same goal.

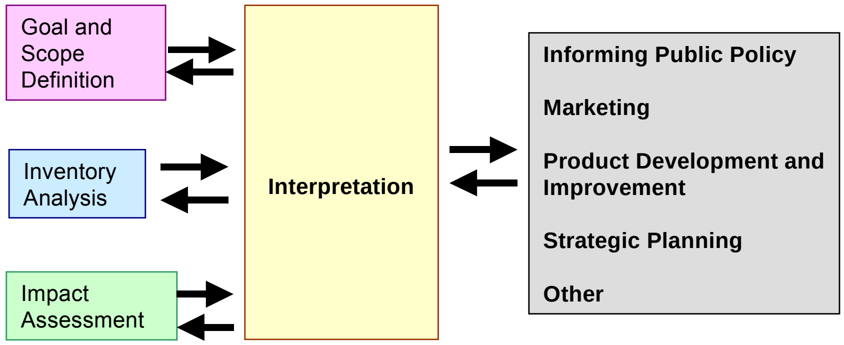


Figure 1. Typical applications and phases of a life-cycle analysis (adapted from Pennington et al., 2004, and based on ISO 14040, 1997)

In the overall benefits framework, health impacts for energy production fuel cycles are based on criteria air pollutants, hazardous air pollutants, and hazardous substances released to water or transferred to disposal sites. Because these substances give rise to both cancer and non-cancer health endpoints, this exploratory assessment employs a single measure of potential harm by translating all health impacts into a single measure of disease burden: the disability- or disease-adjusted life year (DALY). The DALY is a summary measure of the toll exacted by a particular health problem. DALYs combine, for a particular population, the sum of years of life lost (YLL) due to premature death due to a particular cause with estimates of the sum of years lived with disability (YLD) due to the same cause. YLD is weighted by the severity of the condition. A substantial benefit to the DALY approach is that chemicals with different health endpoints can be compared with each other on the same scale of health damage.

To demonstrate the framework for assessing net efficiency benefits for California, this report describes an initial case study based on particulate matter (PM 2.5), nitrogen oxides (NO_x), sulfur dioxide (SO_2), and toxic air pollutants including benzene and two polycyclic aromatic hydrocarbons, benzo(a)pyrene (BaP) and naphthalene. The current mix of energy technologies employed to produce electricity in California provides the emissions baseline used to estimate the net health benefits of increasing the use of insulation in California residences. This exploratory, first-tier scoping study addresses the use of fiberglass attic insulation in existing single-family homes heated by electricity. Therefore, the primary life-cycle inventory data used in this report is restricted to atmospheric emissions of selected pollutants from power plants and from the manufacturing of the energy-efficient end-use technology—i.e., the fiberglass insulation. This study does not focus on indoor sources of exposure or on the associated health effects from the indoor exposure to the chemicals considered in this study as releases to ambient air. Additionally, this research does not consider the economic impacts or other implications of installing the fiberglass insulation in California residences.

1.3. Report Organization

The remainder of this report is organized into three major sections—approach and methods, project results, and conclusions and recommendations. The approach and methods section provides information on the conceptual framework for the LCIA calculations, the models used, and the sources of data for these models. Emphasis here is placed on pollutant emissions, pollutant transport, human exposure, and resulting health effects from energy production in California. There is also an emphasis on how to define emissions and release locations for the current mix of technologies used to produce energy in California. Separate attention is given to insulation manufacture and use—with a focus on both energy saved and environmental emissions resulting from the manufacture of the additional insulation. The results section provides a detailed summary of quantitative findings along with an evaluation of these results. This is followed by a conclusions and recommendations section that summarizes the study's key findings as well as recommendations for follow-on research.

2.0 Project Approach and Methods

The key elements of the framework used to quantify the life-cycle benefits and impacts of energy efficiency are the conceptual model; the computational models and how they are applied; and the sources, types, and values of data used as model inputs. The conceptual framework for allocating impacts was derived from standard methods of life-cycle assessment and comparative risk assessment.

U.S. EPA and California Energy Commission databases were used to determine emissions locations and magnitude. Exposure assessments were based on the output from multimedia (air, water, land) multi-pathway models. These models typically estimate exposure based on the principle of mass balance, which matches emissions to both environmental dispersion and losses through transport and chemical transformation. LCIA relies primarily on regional multimedia models that are applicable over spatial scales from roughly 100 to 100,000 km^2 to estimate human exposure to criteria and hazardous air pollutants. In LCIA it is commonplace to characterize exposures that are representative of an archetypal individual in a given region. Exposure is used to calculate human intake, which is the basis for calculating disease burdens in the population, through the use of the disability-adjusted life years (DALYs) metric. DALYs provide the measure of disease burden in the comparative calculations. A substantial benefit to the DALY approach is that different chemicals can be compared with each other on the same scale of harm.

The following subsections discuss how the research team combined these elements to evaluate the health benefits of energy efficiency. The focus is on (1) technology-specific reductions in power production in California corresponding to increased use of attic insulation and (2) on calculations of how the additional insulation changes exposures to a portfolio of pollutants and the corresponding reduction in disease burden.

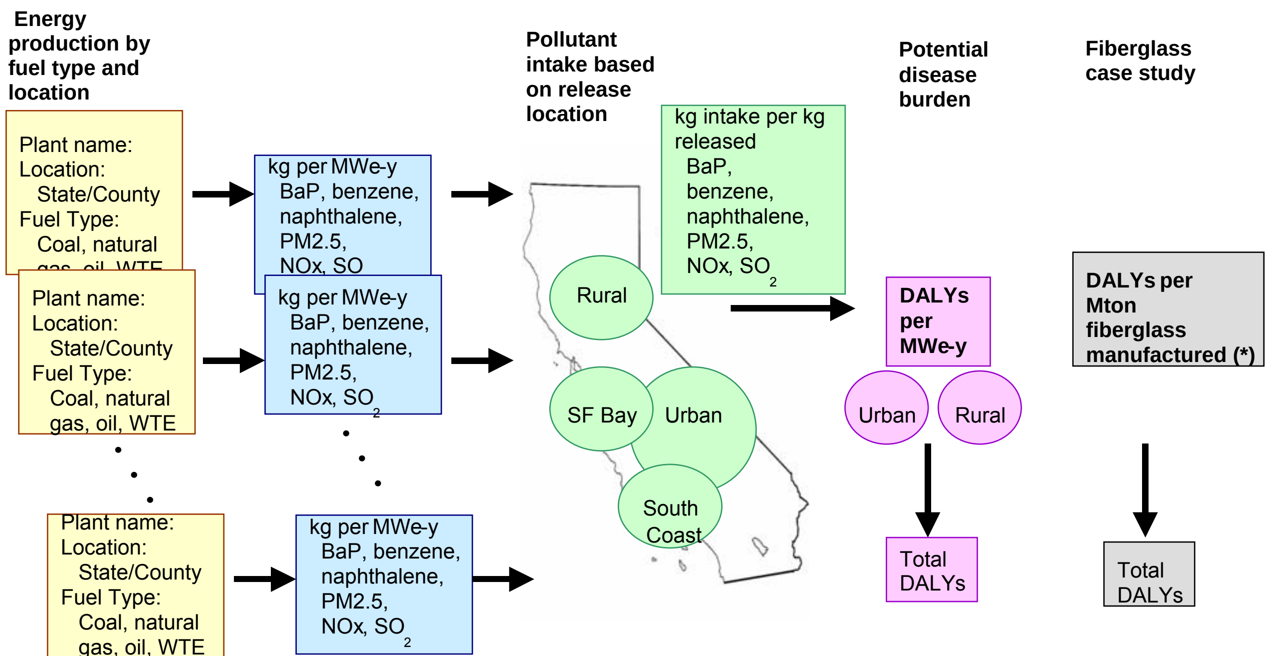
2.1. Scope of the Analysis

In setting the scope of this study, the researchers had to select the portfolio of energy production technologies, the portfolio of demand-side reduction technologies, pollution categories and data, pollutant transport models, assumptions about human exposure to these pollutants, and the health effects categories. To facilitate these selections, the proposed framework was organized around an area of application. The area of application was population exposure to air pollutants attributable to both energy production and demand reduction technologies. The goal was to characterize disease burdens avoided as a result of reduced electricity generation, specifically due to the installation of fiberglass attic insulation in single-family homes in California.

The scope of the analysis included:

- Definition of the conceptual framework.
- Quantification of the amount of electricity generated for consumption in California; the location (county) of this generating capacity; and emissions associated with different power generation technologies.
- Allocation of the health benefits from emissions reductions attributable to greater energy efficiency.

Figure 2 provides a summary illustration of both the scope and key elements of the approach.



* Includes those DALYs avoided due to reduction in electricity usage from the installation of fiberglass insulation, as well as the DALYs associated with the manufacture of the fiberglass insulation. WTE = waste to energy.

Figure 2. The conceptual framework and key elements of this study

2.1.1. Framework Definition—Concept and Approach

Comparisons between impacts of various power production systems and those associated with technologies to improve end-use efficiency must use a consistent framework for assessing environmental transport, human exposure, and health risks. The framework appropriate for addressing this comparison must address the following questions:

- What are the emission rates per unit (MWe-year) of electricity produced? That is, how many kilograms of a pollutant are emitted for each MWe-year of electricity produced by a given type of power plant?

- Which pollutants should be studied?
- Where are these emissions released?
- How are these emissions distributed in the environment?
- What populations are impacted and what is the level of human exposure?
- Where and how should boundaries be set in terms of populations, time, and spatial scale for the assessment?
- What are the potential toxic effects of these exposures and the resulting health burden for California and other populations?
- What are the uncertainties in defining and quantifying the disease burden? How will the study include the model evaluation process needed to identify and characterize these uncertainties?

These questions apply to both the technologies used to produce electrical energy and the technologies used to increase the efficiency of energy use. These questions require source-to-dose assessments that locate all points of chemical release to the environment, characterize mass-balance relationships, and track the contaminants through the entire environmental system to determine the exposure of individuals or populations.

The key challenge for this task was to define a framework that includes sufficient fidelity to the real systems to make reliable classifications about the health impacts of energy systems but to avoid more detail than can be accommodated by existing theory and data. The researchers elected to use methods in the U.S. EPA Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI, version 2) (Bare et al. 2002). In particular, this project relied on the CalTOX multimedia model (version 4.4), which is a key element of the TRACI system (Hertwich et al. 2001). TRACI is the U.S. standard for LCIA.

2.1.2. Portfolio of Energy Production Technologies

Information available from the Energy Commission was used to establish the mix of power generation technologies that provide the major fraction of electricity for California. Each technology was characterized according to (a) power plant technology by fuel type (natural gas, coal, hydroelectric, nuclear, etc.); (b) the location (county) of the production facilities within each power plant fuel type category; (c) the fraction of California energy provided by each combination of location/technology; and (d) pollutant emissions per annual megawatt electric (MWe-y) provided by that technology.

2.1.3. Energy End-Use Reduction Technologies

The impacts of any technology used to reduce energy consumption must also be considered. In this exploratory effort, the case study addresses the use of fiberglass attic insulation in single-family residences heated by electricity. For this project, the important attributes of an end-use technology include (a) the type of technology (insulation, as opposed to lighting, appliances, cool roofs, commercial HVAC, etc.); (b) the location of any production facilities linked to fiberglass insulation manufacture; (c) the fraction of California energy demand reduction experienced at each combination of power plant location/technology; (d) the energy saved

(MWe-y) per functional unit of end-use technology installed (i.e., per kilogram [kg] insulation installed); and (e) pollutant emissions created per functional unit of end-use technology installed (i.e., kg pollutant emitted per kg insulation manufactured).

2.1.4. Pollutant Categories and Human Exposure

Quantifying human exposure begins with selecting pollutants that are important contributors to potential human health hazards. For atmospheric releases, the research team developed emissions estimates for coal, natural gas, oil, and waste-to-energy (WTE) power plants located in California (plus a single plant in Nevada). Emissions factors were also developed for insulation manufacturing—expressing pollutant emissions per tonne of manufactured insulation. Time and funding limitations of this exploratory study forced a focus on a limited number of pollutants. The following six air pollutants were selected for study:

- NO_X
- SO_2
- Particulate matter with a 2.5-μm or lower aerodynamic diameter (PM2.5)
- Benzo(a)pyrene
- Benzene
- Naphthalene

These six pollutants selected are all emitted from various electricity-producing technologies and are responsible for a large fraction of the health impacts in the electricity sector. Also, naphthalene, benzene and benzo(a)pyrene are hazardous air pollutants which have not yet been characterized by any previous health benefits study on the health benefits of increased end-use electricity efficiency. Moreover, they can be incorporated within the TRACI-CalTOX LCIA modeling system.

The atmospheric emissions estimates were used to characterize exposure levels for different geographical population subgroups in California. For the case study here, the state was divided into urban and rural populations. Then the research team used fate and transport modeling to obtain generic urban and rural exposure factors (emission-to-intake factors) for each pollutant. The power plant emissions were then allocated to either an urban or rural population based on the location of the facility. The emission-to-intake factor (also known as the individual intake fraction, or *iFi*; see Bennett et al. 2002a) expresses the ratio of the typical daily exposure within a defined population per unit mass emitted, that is, kg intake/d /person per kg/d emitted. The CalTOX model, which provides fate and exposure factors for TRACI (Bare et al. 2002), was used to calculate this ratio.

2.1.5. Health Effects Categories

Disease burden estimates attributable to pollutant exposures were based on human damage factors (HDFs) (Crettaz et al. 2002; Huijbregts et al. 2005). For each of the pollutants studied, the HDF expresses the disability-adjusted life years lost in the population for each increase of intake, i.e., DALYs per mg intake.

2.1.6. Boundaries for the Time and Spatial Scale of Health Impacts

The atmospheric emissions estimates and resulting disease burden analysis of this study were allocated by dividing the state into urban and rural counties. There were also separate illustrative analyses of the San Francisco Bay Area (SFBA) air basin and South Coast air basin. The analysis was carried out county by county. The power plants were assigned to a county, and the exposure modeling was carried out under either an urban or rural scenario based on the population density of the county. A rural county was defined as having a population density of less than 35 persons/km^2 and any county above that density was defined as urban (Lobscheid and McKone 2004). The SFBA air basin comprises nine counties: Alameda, Contra Costa, Marin, Napa, San Francisco, San Mateo, Santa Clara, Solano, and Sonoma counties. The South Coast air basin comprises four counties: Los Angeles, Orange, Riverside, and San Bernardino (only half of the latter two are actually in the South Coast air basin, but for the purposes of this study, information on the whole county is included).

2.2. Location and Relative Magnitude of Power Plant Emissions

In order to characterize the health impact of emissions reductions due to energy efficiency, this study required a method for allocating emissions changes among the large number of power plants that supply electrical energy in California. The approach used considers installed capacity as a means of ranking the emissions burden by geographic location. Installed capacity for each facility and emissions factors for the fuel and technology used at each facility provide the basis for this calculation. In 2004, slightly over 62 gigawatts electric (GWe) of installed production capacity generated electricity for consumption in California (Energy Commission 2004). This capacity represents a variety of fuel sources. Based on primary fuel sources reported by the Energy Commission (2004), the percent contribution of each of the fuel sources to electric generating capacity in California is shown in Figure 3.

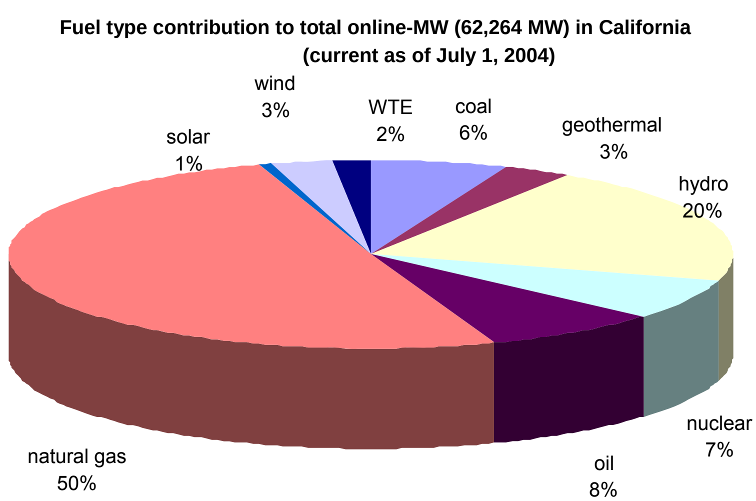


Figure 3. Fuel type contribution to total online-MWe (62,264 MWe) produced and consumed in California. (The pie chart also includes electricity production from the Mohave coal station in Nevada and the Intermountain 1& 2 coal stations in Utah.)

This figure reveals that half the generating capacity in California is from natural gas technologies. Although 3771 MWe (or 6%) of generating capacity comes from coal-fired power plants (including coal plants that burn, as their primary fuel, lignite and petroleum coke and/or crude oil), 86% of this coal-fired capacity is outside of California, i.e., 43% in Utah (Intermountain 1&2) and 43% in Clark County, Nevada (Mohave Generating Station, bordering California and operated by Southern California Edison). Because the Intermountain and Mohave coal plants are under California control, they are included in Figure 3. Of the remaining 13% of coal-derived generating capacity, close to half (47%) comes from coal plants that burn coal (bituminous, subbituminous, and lignite) exclusively. The other half uses coal alternatives such as petroleum coke and/or crude oil within the state of California (amounting to less than 0.5% of the total MWe online generated in California).

The allocations in Figure 3 are based on the assumption that same plant efficiencies apply to all power plants of a certain technology type: e.g., all natural gas–fired power plants are assigned a single conversion efficiency (rather than assigning different efficiencies to individual plants). This study characterizes the emissions resulting from electric power production within California for use in California. In addition, this study includes the emissions from the Mohave Generating Station in Clark County, Nevada, because of its close proximity to the California border and large contribution of energy to California.

To characterize the allocation of emissions avoided due to efficiency-driven reductions in power generation in California, the following two databases were combined:

1. **The Energy Commission's (2004) database** that includes all power plants in California that are one-tenth (0.1) megawatt capacity or larger. This database provides the following information for each plant: the plant name, county of location, owner, operator, the facility type (coal, oil, natural gas, or waste to energy), the general fuel, primary fuel, and the technology employed to generate the reported online MWe for each plant. This information is current as of July 1, 2004. Appendix C of this report provides the full list of plants considered for this study, along with county location, whether or not cogeneration technologies are used, the MWe online, and the classification of the plant's location as "urban" or "rural."
2. **Chemical-specific emission factors (EFs) from U.S. EPA's AP 42 report** (EPA 1995-2000). These data provide consistent, typical, and transparent emission factors for plants fired by oil, natural gas, and coal, as well as those plants burning waste-to-energy (WTE) fuels, such as agricultural and wood waste, landfill gas, and municipal solid waste. This report also provides emission factors for electricity generated from natural gas at redeveloped sites that have had the presence or potential presence of a toxic contaminant, that is, *brownfields* (developed sites) and *greenfields* (undeveloped sites).

These two data sets were used to develop an emissions factor for each generating facility. The primary, as opposed to general, fuel use reported in the Energy Commission's database (2004) was used to generate emissions estimates, and if two or more primary fuels were listed, then an equivalent fraction for each fuel was assumed. In the cases where more than one primary fuel was listed, it was assumed that there was an equal contribution from each fuel type to the total

MWe capacity. Emission estimates [kg/(MWe-y)] for each chemical p_i and plant *j* were based on the following equation:

$$Emissions_{i,j} = \left(\frac{MWt}{MWe}\right)_j \times \frac{EF_{i,j}}{HV_{fuel}} \times CF_{fuel} CF_1 \times CF_2 \times CF_3 \qquad (Eq.\ 1)$$

where:

i designates the pollutant of interest.

j designates the type of power plant (generating electricity from a specific fuel-technology combination).

$(MWt/MWe)_j$ is thermal output (MW) of plant *j* divided by its electrical output (MW) and equal to $1/\eta_e$, with η_e equal to the efficiency of plant *j*. Values for η_e are provided in Appendix A, Table A-1. This analysis did not distinguish between the η_e of the lower heating value (LHV) or higher heating value (HHV) of the fuel. In general, η_e values based on HHV were approximately 5%–10% higher than LHV (EPA 2001). In addition, unless otherwise noted, efficiencies were the electrical, not thermal, efficiency.

$EF_{i,j}$ is the chemical-specific emission factor for chemical *i* from plant type *j*, expressed as kg pollutant per unit quantity of fuel consumed. Table A-2(a-f) in Appendix A lists $EF_{i,j}$ values—in lb/ton coal, lb/1000 gal oil, and lb/10^6 scf (standard cubic feet) of gas—along with their EF rating (A-E; for details on the ratings see the introduction in AP 42, http://www.epa.gov/ttn/chief/ap42/c00s00.pdf). For coal $EF_{i,j}$, this project used the average of the bituminous and subbituminous EF reported.

HV_{fuel} is the heating value of the specific fuel, expressed as Btu/lb coal, Btu/gal oil, Btu/scf natural gas, Btu/scf digester gas, or Btu/scf landfill gas. Heating values are given in Appendix A, Table A-3.

CF_{fuel} is the conversion factor for fuels (5×10^{-4} ton per lb of coal; 10^{-3} lb/gal per lb/1000 gal for oil; and 10^{-6} lb/scf per lb/10^6 scf for gas).

CF_1 is the conversion factor for MWe to Btu (3.413×10^6 Btu/h per MWe).

CF_2 is the conversion factor for hours to years (8760 h/y).

CF_3 is the conversion factor for lb pollutant to kg pollutant (0.455 kg/lb).

Because the Energy Commission's power plant database does not distinguish between bituminous coal and subbituminous coal, emission estimates were either based on an average EF value from the reported EFs from each fuel, where available in the AP 42, or the bituminous EFs. Furthermore, because $EF_{i,j}$'s relevant to petroleum coke and crude oil were not available, the $EF_{i,j}$ for coal and the η_e of coal plants was applied to these fuel sources.

In cases where two or more conversion technologies were reported, e.g., steam and gas turbine, it was assumed that an equal portion of the MWt output was generated from each, based on the available $EF_{i,j}$. With respect to EFs from natural gas–fired plants, where the technology of the power plants was not reported, steam turbine technology was assumed (these emit less chemicals than the stationary gas turbine plants).

For certain fuel-technology combinations, $EF_{i,j}$ values were not available in the AP 42. These included plants relying on enhanced oil recovery (EOR), and NO_x and SO_2 from digester gas technologies and NO_x, SO_2, and benzene from landfill gas fuel technologies. Estimated emissions of these fuel-technology combinations were not accounted for in this study.

2.3. Dispersion, Exposure, and Intake of Emissions to Air

In this study, the CalTOX model was used to characterize the transport, fate, exposure, and uptake for each pollutant released to the atmosphere of either urban or rural environments from power generating facilities used to provide electricity for California. The same approach was also used to assess impacts from insulation manufacturing. This exposure assessment translates emissions to intake for the populations proximate to electrical generating stations. Rather than a site-specific assessment for each power plant, generic urban and rural environments were used.

The study made use of CalTOX version 4.4 (http://eetd.lbl.gov/ied/era/), which was developed at the University of California, Berkeley, and provides fate and exposure assessments for TRACI (Bare et al. 2002). As illustrated in Figure 4, CalTOX is a multimedia, multi-pathway exposure model that tracks the dispersion and dilution of pollutants emitted to air, water, and/or soil. CalTOX has been widely used in the past for chemical classification and multimedia risk assessment. The parameters in the version of CalTOX used in this study have been validated in numerous studies and CalTOX itself has been evaluated using empirical data in field case studies for various chemicals, including BaP (Lobscheid and McKone 2004).

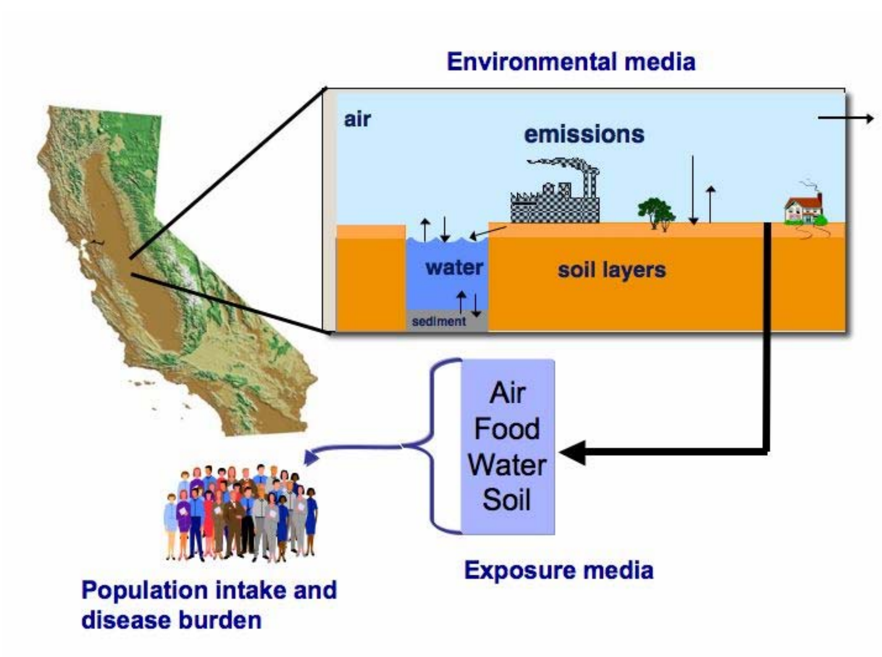


Figure 4. Elements of the CalTOX multimedia fate and exposure model

In general, multimedia fate and exposure models synthesize information about partitioning, reaction, and intermedia transport properties of a chemical in a representative or generic environment with information about the typical individuals exposed. This information is used to assess impacts such as health risk (McKone and MacLeod 2004). In these models, the environment is treated as a set of compartments that are homogeneous subsystems exchanging water, nutrients, and chemical contaminants with other adjacent compartments. Two basic features make compartment models suitable for an integrated model of transport and transformation in multimedia environments: (1) each compartment forms a unit in which one can balance gains and losses attributable to air emissions, transfers to and from other compartments, and chemical transformations, and (2) each compartment forms a unit in which chemical partitioning can be evaluated against equilibrium criteria. A cumulative multi-pathway exposure assessment for humans relates contaminant concentrations in multiple environmental media to concentrations in the media with which a human population has contact (e.g., personal air, tap water, foods, household dusts, and soils). The potential for harm is assessed either as the average daily intake or uptake rate or as time-averaged contact concentration. Multimedia contaminant fate and exposure models have been useful to decision makers because these models provide an appropriate quantitative framework to evaluate our understanding of the complex interactions between chemicals and the environment. The greatest challenge for multimedia models is to provide useful information without creating overwhelming demands for input data or producing outputs that cannot be evaluated.

In the CalTOX model, the fate of a chemical emitted to the environment depends, among other factors, on its physical-chemical properties. Table 1 summarizes physical-chemical properties of the six pollutants that are the subject of this study. These properties include molecular weight (MW); octanol-water partition coefficient (K_{ow}), which is the lipid-to-water solubility ratio; vapor pressure (P_{vap}); water solubility (S_{water}); and diffusion constants in air and water (D_{air} and D_{water}, respectively).

Table 1. Physical-chemical properties of pollutants included in this report

Chemical	MW (g/mole)	K_{ow}	P_{vap} (Pa)	S_{water} (mole/m^3)	D_{air} (m^2/d)	D_{water} (m^2/d)
Benzene	78.1	151	1.3×10^4	22.5	0.76	9.6×10^{-5}
Benzo(a)pyrene	252	2.2×10^6	7.1×10^{-7}	1.0×10^{-5}	0.44	5.3×10^{-5}
Naphthalene	128	2.39×10^3	12.9	2.4×10^{-1}	0.51	7.4×10^{-5}
NO_x [a]	46	2.63×10^{-1}	1.0×10^5	2.2×10^4	0.61	6.9×10^{-5}
SO_2	64	6.31×10^{-3}	1.0×10^5	1.7×10^3	0.61	6.9×10^{-5}
$PM_{2.5}$ [b]	400	0	0	1	0.64	1.3×10^{-4}

[a] Assumes physical-chemical properties of NO_2

[b] In addition to the assumptions listed in this table, separate analyses were run assuming partition coefficients of 10^6 and 10^7 in the ground soil layer (Kd_s), vadose zone layer (Kd_v), aquifer layer (Kd_q), and in surface water sediments (Kd_d).

2.3.1. Calculations of Environmental Dilution

The generic and modular format of the comparative assessment here requires that the dilution calculation provide a dilution factor that expresses the ratio of the long-term average concentration to the emission, $(mg/m^3)/(kg/y)$. CalTOX was configured to calculate dilution factors for power plants located in each of the four regions listed in Table 2.

As is commonplace in LCIA, the researchers assigned releases to generic landscapes that represent archetypal regions but do not necessarily replicate any specific region. In this approach, environmental concentrations were characterized for six cases: (1) the total land area of the urban counties of California, (2) the total land area of the urban counties of California that have at least one electricity generating station, (3) the total land area of the rural counties of California, (4) the total land area of the rural counties of California that have at least one electricity generating station, (5) the South Coast air basin, and (6) the San Francisco Bay Area air basin. Dividing California into these six regions provided a process for assessing the sensitivity of the results to how the emissions are allocated.

Table 2. Population and total area (land and water) of the study regions

Region	Total Area (m^2)		Population	
	Counties with power plants	All counties	Counties with power plants	All counties
Urban area	1.9×10^{11}	2.0×10^{11}	3.3×10^{7}	3.3×10^{7}
Rural area	1.2×10^{11}	2.2×10^{11}	2.2×10^{6}	2.6×10^{6}
South Coast air basin		8.5×10^{11}		1.7×10^{7}
SFBA air basin		2.1×10^{11}		7.0×10^{6}

2.3.2. Human Exposure and Intake

To make the link from emission to intake, the *intake fraction*, or *iF* concept, was applied (Bennett et al. 2002a, 2002b). Intake fraction is the fraction of material released from a source that is eventually inhaled or ingested by the human population in a defined geographic region. For environmental contaminants, the *iF* is the simplest possible expression of the source-to-intake relationship, which is often a complicated function of the attributes of the chemical, the environment, and the population. Bennett et al. (2002a) have suggested a standard formalism for expressing the concept. Here, the individual intake fraction *iFi* is employed. This is the intake fraction for a single representative individual within a defined region. The link between source emissions and intake is the product of the dilution factor obtained and the intake factor that expresses the contact a representative individual has with a diluted concentration in air, water, soil, etc.

The CalTOX model quantifies the source-to-exposure relationship for a system comprising a pollutant defined by its chemical properties and release scenario, the environment within which it disperses, and the potentially exposed population. The nature and extent of multimedia exposures depends largely on human factors and the concentrations of a chemical substance in the contact media. Human factors include all behavioral, sociological, and physiological characteristics of an individual that directly or indirectly affect his or her contact with the substances of concern. Important factors in this regard are contact rates with air, water, food, soils, drugs, etc. Activity patterns, which are defined by an individual's allocation of time spent at different activities and locations, are also significant because they directly affect the magnitude of inhalation exposures to substances present in different indoor and outdoor environments.

The exposure models in CalTOX encompass 23 exposure pathways that relate contaminant concentrations in the multimedia model compartments to concentrations in media with which the human population has contact (i.e., personal air, tap water, foods, household dusts, soils, etc.). Average daily pollutant intake is calculated as the product of the exposure concentrations in these media and an intake factor for inhalation and ingestion that relates the concentration intake for a typical member of the population. For PM2.5, only inhalation exposures were considered; for the other pollutants in this case study, multiple routes of exposure were allowed.

2.4. Estimating and Expressing Disease Burden

Disease burden is a metric that reflects the total amount of healthy life lost within a population due to all diseases found in that population. The calculation of disease burden attributable to pollutant exposures makes use of metrics that have been developed for LCIA, i.e., the human damage factors (HDFs). HDFs express the likelihood of a health consequence (e.g., cancer and/or non-cancer disease burden) resulting from the emission of a particular pollutant (Crettaz et al. 2002). The units of the HDF are effective years of life lost per kg pollutant emitted. Huijbregts et al. (2005) refer to HDFs as characterization factors (CFx). The general approach for calculating an HDF for a substance x, is:

$$HDF_x = EF_x \times FF_x \qquad (Eq.\ 2)$$

EF_x is a severity-based effect factor characterizing both the potential disease burden associated with a lifetime exposure to chemical x, expressed as an equivalent loss of years (i.e., statistical years lost per mg intake of x).

FF_x is the fate factor, or the population intake per unit of emission. The FF_x—defined as the kg(intake)/y per kg(emission)/y—is equal to the *iFi*, multiplied by the population from Table 2 for which that *iFi* applies. The *iFi* is discussed in the previous section.

The effect factor (EF_x) requires consideration of the type of disease, the probability of having that disease following exposure, and the measure of severity of the disease in terms of the equivalent years of life lost as a result of having that disease.

The following subsections review this process for two major disease categories—cancer and non-cancer diseases. It is important to note here that cancer and non-cancer endpoints were explicitly evaluated for each chemical with the exception of PM2.5. This is because PM2.5 has reliable premature-mortality health data available that incorporates both non-cancer and cancer health endpoints. Therefore PM2.5 was not evaluated separately for these health endpoints.

Furthermore, because morbidity endpoints, such as cardiovascular disease and respiratory function, attributable to outdoor air PM2.5 exposures tend to be available only for susceptible populations, such as Medicare enrollees (Dominici et al. 2006), this report focuses on the mortality endpoints. The methodology for PM2.5 is presented following the cancer and non-cancer health endpoint methodologies.

2.4.1. Effect Factor (EF_x) for Cancer

Both Crettaz et al. (2002) and Huijbregts et al. (2005) have proposed methods to determine EF_x for cancer. Crettaz et al. (2002) propose:

$$EF_x(cancer) = \beta_{ED10\text{-}x} \times DALYp \qquad (Eq.\ 3)$$

$\beta_{ED10\text{-}x}$ is the linear low-dose-response slope factor [individual lifetime risk of cancer per (mg/kg BW-day) intake] for chemical *x*, inducing a response over a background of 10% for humans (human equivalents are expressed as h to contrast results based on animals, such as r for rodents). It is obtained from the dose that gives 10% of a population a response (i.e., cancer), the $ED10_{x,h}$ (mg/kg BW/day). So $\beta_{ED10,x} = 0.1/ED10_{x,h}$.

$DALY_P$ is the sum of years of life lost due to death and disability from the cancer caused by *x* (years lost/incidence). The default $DALY_P$ for carcinogens is 6.7 years. Because BaP and benzene are also associated with specific cancers—lung cancer and leukemia, respectively—their specific $DALY_P$ values were also used. Therefore, in addition to the default $DALY_P$ of 6.7 y, 13.0 and 14.6 y were used to estimate EF_x for BaP and benzene, respectively, based on the Crettaz et al. (2002) methodology. Additional assumptions are provided in Table 3. According to Huijbregts et al. (2005),

$$EF_x(cancer) = \frac{1}{ED50_{x,r}} \times p(d \mid \Delta TU) \times DALYp \qquad (Eq.\ 4)$$

Here $ED50_{x,r}$ is the lifetime dose (kg) of substance *x* from exposure route *r* affecting 50% of the exposed human population. $ED50_{x,r}$ is estimated using the $TD50_{x,a}$ from animal experiments, i.e., the daily dose rate [mg/kg(BW)-d] that induces tumors in half of the test animals that would have otherwise been tumor free at no dose. $TD50_{x,a}$ values are available form the Cancer Potency Database (Gold et al. 2005). The animal dose to human dose conversion factors are provided in Table 3.

The term $p(d \mid \Delta TU)$ signifies the probability of occurrence of a disease, *d*, caused by a marginal change in the ambient toxic unit (TU) (note that the term TU has no units). For carcinogens, Huijbregts et al. (2005) use a default $p(d \mid \Delta TU)$ value of 0.03. Huijbregts et al. (2005) use the same definition of DALYp as Crettaz et al. (2002), but because Huijbregts et al. (2005) do not use disability age weighting and discounting, their default $DALY_P$ for a carcinogen is 11.5 years lost as opposed to the 6.7 years used by Crettaz et al. (2002). Huijbregts et al. (2005) also report disease-specific $DALY_P$ values for different chemicals, as given in Table B-1b in Appendix B.

Table 3. Assumptions and conversion factors used to calculate the cancer EF_x

	Crettaz et al. (2002)	Huijbregts et al. (2005)
BW(human) [kg]	70	70
BW (rat) [kg]		0.25
BW (mouse) [kg]		0.03
BR (human) [m^3/d]	20	20
Lifetime (human) [y]	70	75
CF_oral (rat→human)		4.1
CF_oral (mouse→human)		7.0

BW = body weight (kg)
BR: breathing rate (m3/d)
CF_oral (rat→human): oral ingestion conversion factor from rat to human
CF_oral (mouse→ human): oral ingestion conversion factor from mouse to human

For chemicals which do not have an available $TD50_{x,a}$ value, Huijbregts et al. (2005) estimate $ED50_x$ from the q_x*, the U.S. EPA cancer potency factor:

$$ED50_x = 0.8 \times \frac{1}{q_x^*} \qquad (Eq.\ 5)$$

As seen from Eq. 3, Crettaz et al. (2002) rely on the $\beta_{ED10,x}$ that can easily be derived from the $ED10_{x,h}$. But because $ED10_{x,h}$ values are not reported for the six chemicals in this study, the $\beta_{ED10,x}$ for these substances was estimated directly from the U.S. EPA q_1*, the 95th% upper confidence bound on the linearized multistage model slope factor q_1, using a regression used by Crettaz et al. (2002):

$$\beta_{ED10} = 0.5 \times q_1^* \qquad (r^2 = 0.95;\ n\ 44) \qquad (Eq.\ 6)$$

In cases where q_1* is not available, Crettaz et al. (2002) have provided the following two equations for estimating $ED10_{x,h}$ from the $TD50_{a(animal),x}$:

$$ED10_{x,h} = \frac{TD50_{a,x}}{40} \qquad \text{(theoretical; one-hit model of extra risk)} \qquad (Eq.\ 7)$$

$$ED10_{x,h} = \frac{TD50_{a,x}}{25} \qquad \text{(empirical; } r^2 = 0.75;\ n=37\text{)} \qquad (Eq.\ 8)$$

2.4.2. Effect Factor (EF_x) for Non-cancer Effects

The effect factors, EF_x, for non-cancer endpoints were obtained using the approach of Pennington et al. (2002) based on the $ED10_{x,h}$ for non-cancer endpoints and including threshold effects:

$$\beta_{ED10,x} = 0.1/(ED10_{x,h} - Thr) \qquad (Eq.\ 9)$$

Thr is the biological threshold level (mg/kg-BW/day), and other factors are as defined above.

Because BaP and naphthalene are primarily carcinogens and their overall EF and DALYs are dominated by the cancer EF, this report only accounts for the non-cancer disease burdens of benzene, NO_x, and SO_2. For benzene, the $ED10_h$ was derived from the benchmark dose computation (BMD, not BMDL) from the exposure-response data on decreased absolute lymphocyte count (ALC) reported by Rothman et al. (1996). Based on the U.S. EPA benchmark dose software (v1.3.2), a BMD of 3.34 parts per million (ppm)—converted to an $ED10_h$ of 3.0 mg/kg-BW/d—was derived and used as an estimator of $ED10_h$.

For NO_x and SO_2, the $ED10_h$ was estimated from the following equation reported in Pennington et al. (2002):

$$ED10_h = 0.99\ (RfD) + 1.8 \qquad (r^2 = 0.88;\ n{=}12) \qquad \text{(Eq. 10)}$$

The *RfD* is the U.S. EPA reference dose, which is interpreted as a safe dose. For this study, RfD values for NO_x and SO_2 were derived from the inhalation non-cancer risk values reported in the *Scorecard* database (Environmental Defense, 2006a and 2006b, respectively). The non-cancer inhalation risk value for NO_2 was assumed to apply to NO_x.

Because RfD values do not permit inter-chemical comparisons, the ED10 approach proposed by Pennington et al. (2002) was used. The ED10 approach follows the approach to assess carcinogen health effects and is based on bioassay data. The factor of 10 difference between the three non-cancer disease categories proposed by Pennington et al. (2002) comes from the subjective scaling proposed by the International Life Science Institutes panel (Burke et al. 1996). Because cancer effects are also included in the Category 1 effects, the factor of 10 scaling was applied to 6.7 years per disease incidence to derive the Category 2 and 3 non-cancer DALYs. Therefore the default DALYp for a non-cancer substance falls into one of the following three categories:

- Category 1 (irreversible life-shortening effects, e.g., mutations, teratogenic effects, and reproductive effects) — 6.7 y lost/incidence
- Category 2 (probably irreversible/life-shortening effects, including immunotoxicity, neurotoxicity, kidney damage, liver damage, heart disease, pulmonary disease) — 0.67 y lost/incidence
- Category 3 (reversible/non-life shortening effects, including irritation and sensitization) — 0.067 y lost/incidence

Because most of the known non-cancer health effects from exposures to benzene, NO_x, and SO_2 likely fall into categories 2 or 3, this study used the EF_x , and the resulting HDFs, from these disease categories.

2.4.3. *Effect Factor (EF_x) for PM2.5*

For PM2.5, the Crettaz et al. (2002) and Huijbregts et al. (2005) cancer methodologies were adapted to reflect general premature-mortality effects. This was selected as the appropriate method because morbidity endpoints, such as cardiovascular disease and respiratory function, attributable to outdoor air PM2.5 exposures tend to be available only for susceptible populations (Dominici et al. 2006), not an archetypal individual. The EF_x for PM2.5 was based on the finding that a 1 $\mu g/m^3$ increase in annual PM2.5 mean concentrations leads to a 0.4% increase in premature deaths (Pope et al., 2002). This translates to a β_{ED10} of 7.0 / (mg/kg BW/d) by the Crettaz et al. (2002) methodology, and results in an EF_x value of 3.1×10^{-5} DALY/mg intake, assuming a $DALY_P$ of 8.0 years lost/incidence of a premature death (Cohen et al. 2005). By the Huijbregts et al. (2005) methodology, the EF_x value for PM2.5 is 6×10^{-6} DALY/ mg intake, assuming the default $DALY_P$ of 11.5 years lost and default $p(d|\Delta TU)$ value of 0.03.

2.5. Energy and Emissions Reductions Resulting from Residential Fiberglass Attic Insulation

According to the U.S. Department of Energy, up to 30% of a home's energy loss is due to improper or inadequate insulation (U.S. DOE 2006). Fiberglass insulation is commonly installed in attics and cathedral ceilings to combat this large heat loss and is therefore the energy efficiency technology considered here. Fiberglass insulation is sold mostly in rolls and batts, although loose-fill, which is blown into spaces, can also be made of fiberglass. This case study does not consider installation of rigid foam insulation, which is generally used in buildings requiring higher R-values[1] or buildings with space limitations.

To estimate the emissions reductions and subsequent reductions in disease burden from installing additional fiberglass insulation in single-family homes in California, this study relied primarily on housing characteristics provided by the 2001 Database for Energy Efficiency Resources (DEER) Update Study (Energy Commission 2001). As shown by the DEER study, single-family housing characteristics in California vary dramatically with the age of the house. Therefore, this project categorized housing stock into three vintages—pre-1978, 1978 to 1992, and 1992 to the present—and used the median values for each vintage (based on the DEER study data) to represent those homes. Since the study focuses on power plant emissions, only houses heated by electricity were considered.

As a first step in determining the decreased power plant emissions that would result from increased fiberglass insulation in single-family residences, this study estimated the difference in energy consumption (ΔEnergy [Btu/yr]) between electrically heated homes with current insulation levels and electrically heated homes with the increased insulation levels recommended by DOE. The method used for calculating ΔEnergy is given by the following equation:

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1. R-value is a measure of a material's ability to impede heat flow. The higher the R-value, the more effective the insulation.

$$\Delta Energy = \left(\frac{1}{R_{baseline}} - \frac{1}{R_{rec}}\right) \frac{1}{\left[\frac{{}^{o}F \times ft^{2} \times hr}{Btu}\right]} \times Area_{roof}\left[ft^{2}\right] \times HDD\left[\frac{{}^{o}F \times d}{yr}\right] \times CF_{d \to hr}$$

(*Eq. 11*)

$R_{baseline}$ is the baseline R-values for homes heated with electricity reported in the 2001 DEER study and summarized in Table 4.

R_{rec} is the additional attic insulation needed to reach the latest DOE-recommended insulation requirements. R_{rec} applies to "Zone 3" insulation zones, which cover most of California (DOE 2002). R_{rec} is 49 ft^2-hr ^{o}F/Btu for attic insulation in homes heated with electricity and 38 ft^2-hr ^{o}F/Btu for cathedral ceilings in homes heated with electricity.

$Area_{roof}$ (ft^2) is the median roof area summarized in Table 5. In addition, this case study included the cathedral ceiling area as part of the roof area. Cathedral ceilings are present in homes built after 1992 (Energy Commission 2001), and their area is assumed to be 25% of the total footprint area, approximately 1,376 ft^2 (the median of the total footprint area in the climate zones in California reported in the DEER 2001 study with a range of 1,177 to 1,852 ft^2 (Energy Commission 2001).

HDD is the heating degree days (^{o}F-d) for one year. The assumed value for HDD in this study is 2,700 (the median HDD, base 68 F) from the DEER 2001 report (Energy Commission 2001).[2]

$CF_{d \to hrs}$ is the conversion factor from day to hours.

This study reports an estimate of the decrease in electricity demand resulting from the installation of fiberglass insulation with R_{rec} for each single-family home selected from a given house-age category. These ΔEnergy (Btu/y) estimates are given in Table 6.

Table 4. Distribution of attic (and cathedral ceiling for those housing units built after 1992) insulation R-values (ft^2-hr ^{o}F/Btu) for electricity-heated homes from the 2001 DEER study (Energy Commission 2001)

Climate Zone	pre-1978	1978–1992	1992–present
North Coast	5.1	28	30
South Coast	5.9	21.5	30
South Inland	5.3	23.5	30
Central Valley	5.3	20.1	38
Desert	5.3	21.3	38

	Median
pre-1978	5.3
1978–1992	21.5
1992–present	30

2. In this case, heating degree days were calculated using a reference temperature of 68°F (20°C).

Table 5: Median Area$_{roof}$ (ft^2) of single-family housing units in California from DEER 2001 (Energy Commission 2001)

Climate Zone	Pre-1978	1978–1992	1992–1998	Post-1998
North Coast	1591	1904	2164	2296
South Coast	1528	2064	2270	2393
South Inland	1636	1811	2118	2423
Central Valley	1528	1704	2056	1949
Desert	1555	1741	1643	2161
		Median		
pre-1978		1555		
1978–1992		1811		
1992–present		2163		

Table 6. Average household energy savings associated with increased insulation for single-family homes (Btu/year)

pre-1978	1.7×10^7
1978–1992	2.7×10^6
1992–present	1.4×10^6 [a]

[a] Includes both attic and cathedral ceiling insulation

The total energy reduction (Btu) for the entire housing stock in California was estimated based on the average of two housing stock distributions studies (U.S. Census of Population and Housing 2000 and EIA 2005) for each house-age category, as shown in Table 7.

Table 7. Distribution of electricity-heated homes for the western region of the US[a]

pre-1978	34%
1978–1992	43%
1992–present	12%

[a]The western region includes Arizona, Colorado, Idaho, Montana, Nevada, New Mexico, Utah, Wyoming, Alaska, California, Hawaii, Oregon, and Washington (U.S. Census Bureau 2005).

The distribution of fossil fuel electricity production was assumed to follow the current distribution of in-state sources of electricity generating capacity, as shown in Figure 3. Because coal-generated electricity is mostly from the Mohave and Intermountain power plants, approximately 3% of pollutant emissions resulted from electricity generated from the "rural" region Mohave power plant that is located very close to the California-Nevada border.

The magnitude of emissions eliminated for each chemical *i*, $\Delta emissions_i$ (kg/y), as a result of increasing fiberglass attic insulation was estimated as:

$$\Delta emissions_i = \Delta Energy \times emissions_i \times t_{insulation} \times CF_{Btu \rightarrow MWe} \qquad (Eq.\ 12)$$

where:

$\Delta Energy$ (Btu/y) is given by Equation 10 above

$emissions_i$ are the total California emissions for each chemical *i*, per MWe, [kg/(MWe-y)] and obtained using the approach in Section 2.2.

$t_{insulation}$ *(y)* is the lifetime of the fiberglass insulation, assumed to be 50 years.

$CF_{Btu \rightarrow MWe}$ is the conversion factor from Btu to MWe-y (3.345 x 10^{-11} MWe-y per Btu).

The Δemissions was estimated separately for urban and rural power plants in California. These estimates of emissions averted were then divided by the respective MWe from the fuel source in a given region, e.g., the total MWe generated from natural gas in urban regions.

The final step of the calculation was to report the DALYs saved over the lifetime of the fiberglass insulation, per megatonne (Mt) of insulation installed. This was based on the amount of insulation to reach R_{rec} levels, i.e., 1.04 Mt in urban and 0.078 Mt in rural electricity-heated homes. The DALYs are calculated based on the human damage factors (DALYs per kg emitted), as described in Section 2.4.

2.6. Emissions from Fiberglass Manufacturing

In addition to the power plant emissions avoided through the use of insulation, the emissions from the insulation's manufacture must be quantified in order to determine the net health benefit of this energy efficiency measure. Emissions associated with insulation manufacture include both direct emissions from the manufacture of the fiberglass insulation and indirect emissions from *energy* required to manufacture this insulation. A preliminary analysis indicates that the emissions from energy needed to manufacture insulation are negligible compared to emissions from either the insulation manufacturing process or emissions from the energy saved due to insulation use. The electrical energy used to manufacture 1.1 Mt of insulation is approximately 3.1×10^{10} MJ (based on an estimate of 27.9 MJ/kg for the embodied energy of fiberglass materials reported by Franklin Associates (1991). This amount is three orders of magnitude less than the 6.0×10^{13} MJ of electrical energy saved over the 50-year assumed lifetime of the insulation. Therefore the focus here is only on manufacturing emissions, and not on an explicit analysis of emissions added by electrical energy to produce insulation.

The emissions associated with manufacturing fiberglass insulation arise from the various steps outlined in Figure 5. Manufacturing emissions are estimated according to:

$$Emissions_{fiberglass,i} = EF_{fiberglass,i} \times \rho_{fiberglass} \times V_{insulation} \qquad (Eq.\ 13)$$

where:

$EF_{fiberglass,i}$ is the emission factor of pollutant.

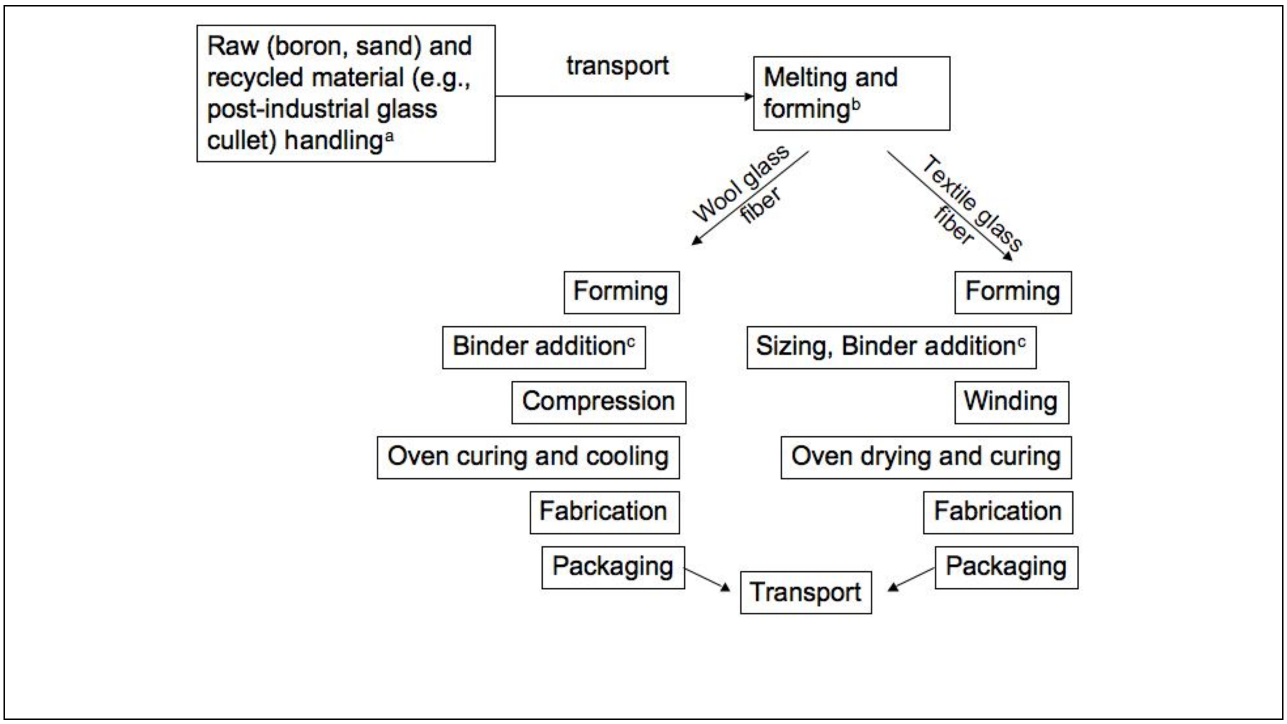
i [kg pollutant/tonne insulation, finished product] is as reported in the U.S. EPA AP 42 (EPA 1985).

$\rho_{fiberglass}$ is the density of fiberglass (9 kg/m^3; EPA 1985).

$V_{insulation}$ is the volume of installed insulation needed to meet the DOE-recommended R-values for insulation in California (i.e., a "Zone 3" region) (DOE 2002).

The baseline R-values are given in Table 4. Table 5 displays the total surface area requiring insulation. This area was multiplied by an average R-value per inch of 3.25 corresponding with fiberglass batts and blankets.

The HDFs (DALYs per kg insulation manufactured) associated with the chemical emissions of the fiberglass insulation were calculated using the same chemicals and methods described for power plant emissions. The DALYs caused by the insulation manufacture were compared with the DALYs saved over the lifetime of the fiberglass insulation—estimated as 50 years.



[a] Includes extraction, storing, crushing, weighing, and mixing
[b] Includes marble forming, annealing, storage, shipment, marble melting
[c] Typically phenol formaldehyde (dissipates and captured by pollution control equipment)

Figure 5. Materials and processes involved in the manufacture of fiberglass insulation (adapted from EPA 1985)

3.0 Project Results

The results of this project are presented in four steps. First, the magnitude and location of emissions for the pollutants of concern are presented as cumulative emissions to California urban and rural regions in kg/(MWe-y). Next, the two elements of the HDF are considered. Human exposure potential is presented as the individual intake fraction, i.e., the fraction of kg/(MWe-y) that is taken into the population. The effect factor is expressed as DALYs attributable to combined urban and rural emissions. Then this information is used to determine the reduction of emissions and disease burden attributable to increasing attic insulation in California. Finally, the disease burden attributable to the manufacture of the fiberglass insulation used is estimated and compared to the disease burden averted.

3.1. Magnitude and Location of Emissions

California's in-state fossil-fuel and WTE generating capacity comprises a total of 3.1×10^4 MWe in urban regions and 7.1×10^3 MWe in rural regions; these figures include the Mohave power plant (see Section 2.2). The power plants supplying this electricity are listed in Appendix C of this report.

Table 8 lists for each candidate pollutant the estimated range of emissions from California power plants for urban and rural regions . Ranges are provided to account for uncertainty in emissions due to variations in reported plant efficiencies (provided in Appendix A Table A-1). These ranges are within the same order of magnitude in each region for each pollutant from plants powered by a given fuel type. Because the San Francisco Bay Area and South Coast air basins are characterized as urban regions, they have emissions estimates per MWe-y that are most similar to those estimated for urban regions (see Table 8 c and d).

The fact that the efficiencies of coal plants vary over a very small range (as can be seen in Table A-1) is reflected in the narrow range of the emissions per MWe-y in the urban regions (Table 8 a, c, and d). Because all of the coal-fired plants located in rural regions use cogeneration technologies and this study located only one efficiency for this fuel-technology combination (0.4, Table A-1), there is a single emissions value in place of a range for these plants in Table 8b.

The total emissions from in-state power plants (plus the Mohave power plant) estimated in this report are most likely higher, not lower, than actual emissions. This conclusion is drawn from the fact that NO_x and SO_2 emissions, which are available from the Emissions and Generating Resource Integrated Database (eGRID) (EPA 2003) are 4.2 and 1.3 Mt per MWe-y, respectively, for California for the year 2000. EPA's eGRID relies on AP 42 emission factors for power plants that do not report emissions. In comparison to the eGRID emissions, the median California-wide emissions of NO_x and SO_2 estimated from the primary fuel/technology power plants in this report are 8.4 Mt of NO_x and 2.5 Mt SO_2, per MWe-y, for 2004. eGRID does not report emissions of other pollutants of interest in this study. However, for both NO_x and SO_2, the emissions estimated in this report are within a factor of two from eGRID, which is reasonable given the uncertainties inherent in these calculations.

In addition, although this report relies on the assumption that installed capacity is equivalent to generation, the resulting total estimated MWe-y generated in California from each fuel-technology combination compares well with that reported in eGRID, i.e., within a factor of two for coal and WTE/other fossil, and within a factor of three for natural gas technologies (EPA 2003). The one exception is for oil-fueled generation. The MWe generated from primarily oil-fueled power plants estimated by the Energy Commission (2004) database is an order of magnitude greater than that reported in eGRID, i.e., 5000 MWe-y compared to 300 MWe-y (EPA 2003). This is most likely due to fuel classification uncertainties. For example, at least four power plants (ranging between 560–2087 MWe-y capacity in the Energy Commission database (2004) are labeled as 100% natural gas–fired plants in eGRID, whereas the Energy Commission database (2004) reports distillate oil as their 'primary fuel.' These four plants—Alamitos, Etiwanda, Huntington Beach, and Mandalay—are included in Appendix C of this report. Because distillate oil combustion emits much more SO_2 and NO_x than natural gas combustion, the result is higher estimates of SO_2 and NO_x emissions per functional unit, MWe-y, than if these four plants were assumed to burn natural gas.

The authors of this report did not focus on specific power plants. But in order to assess the reliability of the emissions used in the study, the authors used the plant-specific emissions reported for the 1640 MWe-y large-scale Mohave coal-fired power plant for comparison. Environmental Defense (2005) estimates annual emissions from this plant of 39,100 tons of SO_2 and 19,200 tons of NO_x. Additionally, the Clean Air Markets database available from the EPA's eGRID website reports similar emissions for the Mohave coal plant in 2004: 43,600 tons of SO_2 and 20,900 tons of NO_x (EPA 2003). Based on the methods and data sources applied in this report, this facility released 41,000 tons of SO_2 and 30,000 tons of NO_x in 2004.

Although the emissions factors and methods vary in each of these approaches, they all provide very similar results and increase confidence about the reliability of the emissions estimates of this report. The slightly higher NO_x emissions reported here are most likely due to the higher emissions factor data from the AP 42, 0.54 lbs/MMBtu (input) in comparison with 0.41 lbs NO_x/MMBtu (input) specific to the Mohave coal plant, available from the eGRID database. Therefore, it is important to note that the ranges listed in Table 8 may not fully reflect the range of uncertainty in emissions factors.

Table 8. Emissions estimates (kg/MWe-y) from coal, natural gas, oil, and WTE primary fuel–powered electricity generating plants in different regions of California

a) Urban Regions

	Coal	**Natural Gas**	**Oil [a]**	**WTE [b]**
Benzo(a)pyrene	2.97×10^{-4} – 3.03×10^{-4}	1.6×10^{-2} – 2.7×10^{-2}	1.3 – 3.6	n/a
Benzene	1.5 – 1.7	1.5×10^{-1} – 2.6×10^{-1}	9.8×10^{-1} – 2.7	5.2×10^{-1} – 1.3
Naphthalene	1.5×10^{-2} – 1.7×10^{-2}	2.1×10^{-2} – 3.9×10^{-2}	7.1×10^{-1} – 1.9	n/a
NO_x	1.6×10^{4} – 1.7×10^{4}	4.0×10^{3} – 7.7×10^{3}	1.2×10^{4} – $3. \times 10^{4}$	4.2×10^{3} – 1.1×10^{4}
PM2.5	3.4×10^{3} – 3.8×10^{3}	35.1 – 58.9	1.8×10^{2} – 4.5×10^{2}	n/a
SO_2	2.2×10^{4} – 2.5×10^{4}	39.1 – 69.4	6.6×10^{3} – 1.6×10^{4}	1.1×10^{3} – 2.9×10^{3}

b) Rural Regions

	Coal [c, d]	**Natural Gas**	**Oil [a]**	**WTE [b]**
Benzo(a)pyrene	5.5×10^{-5}	2.7×10^{-2} – 5.0×10^{-2}	9.8×10^{-1} – 2.8	n/a
Benzene	1.9*	1.7×10^{-1} – 3.1×10^{-1}	1.4 – 3.8	3.4×10^{-1} – 4.9×10^{-1}
Naphthalene	1.9×10^{-2}	2.1×10^{-2} – 4.0×10^{-2}	9.1×10^{-1} – 2.5	n/a
NO_x	2.0×10^{4}	3.8×10^{3} – 7.2×10^{3}	1.5×10^{4} – 4.0×10^{4}	2.3×10^{3} – 3.3×10^{3}
PM2.5	4.2×10^{3}	8.2×10^{1} – 1.5×10^{2}	2.3×10^{2} – 5.8×10^{2}	n/a
SO_2	2.0×10^{4}	4.7×10^{1} – 8.7×10^{1}	7.7×10^{3} – 1.9×10^{4}	7.3×10^{2} – 1.1×10^{3}

c) San Francisco Bay Area Air Basin

	Coal [e]	Natural Gas	Oil [a]	WTE [b]
Benzo(a)pyrene	4.2×10^{-5} – 5.0×10^{-5}	2.0×10^{-2} – 3.1×10^{-2}	1.3 – 3.6	n/a
Benzene	1.5 – 1.7	1.4×10^{-1} – 2.2×10^{-1}	1.3 – 3.6	5.6×10^{-1} – 1.2
Naphthalene	1.5×10^{-2} – 1.7×10^{-2}	2.0×10^{-2} – 3.3×10^{-2}	9.0×10^{-1} – 2.5	n/a
NO_x	1.2×10^{-4} – 1.4×10^{-4}	3.9×10^{3} – 7.0×10^{3}	1.4×10^{4} – 4.1×10^{4}	3.9×10^{3} – 8.3×10^{3}
PM2.5	3.2×10^{3} – 3.8×10^{3}	42.6 – 65.4	2.1×10^{2} – 6.0×10^{2}	n/a
SO_2	2.1×10^{4} – 2.5×10^{4}	38.6 – 62.4	6.9×10^{3} – 2.1×10^{4}	1.2×10^{3} – 2.6×10^{3}

d) South Coast Air Basin

	Coal	Natural Gas	Oil [a]	WTE [b]
Benzo(a)pyrene	5.1×10^{-5} – 5.5×10^{-5}	1.4×10^{-2} – 2.3×10^{-2}	1.3 – 3.6	n/a
Benzene	1.7 – 1.9	1.1×10^{-1} – 2.0×10^{-1}	0.9 – 2.6	0.4 – 1.2
Naphthalene	1.7×10^{-2} – 1.9×10^{-2}	1.9×10^{-2} – 3.7×10^{-2}	0.7 – 1.8	n/a
NO_x	1.9×10^{4} – 2.1×10^{4}	4.0×10^{3} – 8.2×10^{3}	1.1×10^{4} – 2.9×10^{4}	4.2×10^{3} – 1.1×10^{4}
PM2.5	3.8×10^{3} – 4.2×10^{3}	31.1 – 51.6	1.8×10^{2} – 4.3×10^{2}	n/a
SO_2	2.5×10^{4} – 2.8×10^{4}	43.3 – 78.8	6.5×10^{3} – 1.5×10^{4}	9.9×10^{2} – 2.7×10^{3}

n/a: "not available," referring to emissions factors from primary fuel technology

[a] Distillate and diesel

[b] Digester, landfill, and natural gas only

[c] Same whether or not Mohave plant is included

[d] All rural coal plants were cogen, for which only one efficiency value was found; hence rural coal plants have a single emissions value rather than a range.

[e] Petroleum and crude oil as primary fuel

3.2. Levels of Human Exposure

The levels of human exposure are characterized in terms of the individual intake fraction, *iFi*. The *iFi* value ranges reflect both the variability of emissions estimates (kg/y) in each region and the variability in human exposure factors used in CalTOX. The relationship between the variance of *iFi* estimates and input variances, which reflect uncertainty and variability, can be determined using one of a number of variance propagation methods (Morgan and Henrion 1990). In this study, Monte Carlo sampling provided the method for propagating parameter variance into outcome (*iFi*) variance. In a standard Monte Carlo analysis, simple random sampling is used to select each member of the set parameter value realizations. Each model input parameter is represented by a probability-density function that defines both the range of values that the input parameters can have and the probability that the parameters are within any subinterval of that range. Each input is represented by a cumulative distribution function in which there is a one-to-one correspondence between a probability and a value. A random number generator is used to select probability in the range of 0 to 1. This probability is then used to select a corresponding parameter value.

Monte Carlo sampling was performed with the program Crystal Ball v 5.0. All variable parameters in CalTOX were run probabilistically, and the power plant emissions to the atmosphere (according to Equation 1) were input as a Beta distribution with both shape parameters set to two and the range defined by the minimum and maximum of emissions derived from the fuel-plant efficiencies reported in Table A-1 of Appendix A. The full distributions of the *iFi* for each pollutant in each region are provided in Appendix B, Figures B-1 through B-6. The median values of the cumulative (all route) *iFi* distributions were used for the comparative assessments presented below. The median was selected because it is essentially the same as the geometric mean, which is more appropriate when input parameters have large and logarithmic variations. Because this study was concerned with an archetypal individual living in a given region, the median values are considered a more representative measure of intake.

Table 9 summarizes the pollutant and region-specific *iFi* values used for this study. For all six pollutants considered, with the exception of BaP, only the inhalation pathway is a significant contributor to overall intake. Therefore, the total (ingestion + inhalation) intake and inhalation-only median *iFi*s are presented separately for BaP in Table 9. For BaP in each region considered, the contribution to overall *iFi* due to inhalation intake was ~1.3% of the total intake (ingestion and inhalation) at the median result. For PM2.5, the *iFi* was sensitive to the soil/water distribution coefficient, (K_d [L/kg]) used for the surface soil layer. In Appendix B (Figure B-6), distributions based on K_d values of 10^6 and 10^7 are presented for completeness. However, the distributions based on the two K_d values are nearly identical. In Table 9, the median *iFi* values based on urban (all counties, and also for those counties with at least one power plant) and rural counties (all counties) are most similar. The *iFi* distributions for rural counties with power plants have slightly higher values than the urban and rural (all counties) regions because of the smaller spatial extent of these counties. Smaller spatial scale primarily explains why the *iFi* values are largest in the SFBA air basin.

Table 9. Median values of the *iFi* for each pollutant in each region[a]

	Urban[b]	Rural—All Counties	Rural—Counties with Power Plants	South Coast Air Basin	San Francisco Air Basin
BaP (total = ingestion + inhalation)	4.2×10^{-13}	3.6×10^{-13}	6.7×10^{-13}	9.5×10^{-13}	3.7×10^{-12}
BaP (inhalation only)	5.4×10^{-15}	4.7×10^{-15}	8.9×10^{-15}	1.2×10^{-14}	4.9×10^{-14}
Benzene	2.9×10^{-13}	2.6×10^{-13}	4.0×10^{-13}	5.2×10^{-13}	1.3×10^{-12}
Naphthalene	5.8×10^{-14}	5.1×10^{-14}	9.0×10^{-14}	1.3×10^{-13}	4.4×10^{-13}
PM2.5[c]	1.0×10^{-13}	9.2×10^{-14}	1.7×10^{-13}	2.2×10^{-13}	7.1×10^{-13}
NO_x [d]	1.1×10^{-13}	9.7×10^{-14}	1.6×10^{-13}	2.3×10^{-13}	7.3×10^{-13}
SO_2	2.1×10^{-13}	1.9×10^{-13}	3.2×10^{-13}	4.1×10^{-13}	1.2×10^{-12}

[a] Note that *iFi* is a ratio and therefore has no units.

[b] Same *iFi* distributions result whether analysis considers only the population and area of urban counties with power plants, or all urban counties

[c] Same median *iFi* whether K_d of PM2.5 is 10^6 or 10^7 (L/kg)

[d] Estimated by NO_2

3.3. Results for the Disease Burden Calculations

3.3.1. Effect Factors (EF_x) for Cancer and Non-cancer Diseases

For health effects associated with cancer, non-cancer diseases, and PM2.5-related premature mortality, both the Crettaz et al. (2002) and Huijbregts et al. (2005) approaches were considered in order to select an effect factor to characterize the HDF. The EF_x from each method was calculated and converted to its logarithmic value. Then the log mean (midpoint of the maximum and minimum of the logarithms, divided by two) was computed. With the exception of PM2.5, the EF_x nearest to the computed log mean value was selected and is reported in Table 10. For PM2.5, only one value by each method was estimated and the midpoint is given in Table 10. Appendix B, Table B-1, provides the complete set of EF_x derived by the Crettaz et al. (2002) and Huijbregts et al. (2005) methods (Tables B-1a and B-1b, respectively). For carcinogens, because of the selection criteria for the appropriate EF_x value, the values selected for BaP and benzene are based on the q_1* and the default DALYp of 6.7 years, whereas for naphthalene, the EF_x is based on the Huijbrejts et al. (2005) methodology.

Table 10 provides some insights of interest for making the HDF calculation. First, it reveals that when the EF_x for non-cancer effects for benzene are based on Category 2 diseases, one obtains nearly the same value as for the cancer EF_x. To obtain EF_x for nitrogen dioxide (NO_2) and sulfur dioxide (SO_2), the Huijbregts et al. (2005) method requires either a no-observed-effect level (NOEL) or the lowest-observed-effect level (LOEL). But these are not reported for NO_2 and SO_2. Thus, a comparison of non-cancer HDFs with the Pennington et al. (2002) analysis for these two chemicals was not possible.

Table 10. The EF_x estimates for each pollutant

	EF_x Derivation Comment	EF_x (DALYs/mg intake)
Cancer		
Benzene	Lower bound of range on q_1* (inhalation—>oral); Crettaz et al. (2002) method	1.4×10^{-8}
BaP	Upper bound of q_1* (oral) reported in EPA's Integrated Risk Information System IRIS; Huijbregts et al. (2005) method	5.0×10^{-6}
Naphthalene	Specific DALYe and p(d|ΔTU) for stomach cancer (0.035, 13.6); Huijbregts et al. (2005) method	1.1×10^{-8}
Non-cancer		
Benzene	BMD from Rothman et al. (1996) for decrease in absolute lymphocyte count	
	Category 2:	1.2×10^{-8}
	Category 3:	1.2×10^{-9}
NO_x	ED10h estimated from the inhalation non-cancer risk values[a] of NO_2 (5.7×10^{-3} mg/kg BW/d, Environmental Defense 2006a)	
	Category 2:	9.9×10^{-8}
	Category 3:	9.9×10^{-9}
SO_2	ED10 estimated from the inhalation non-cancer risk value[a] (1.9×10^{-1}mg/kg BW/d, Environmental Defense 2006b)	
	Category 2:	3.1×10^{-9}
	Category 3:	3.1×10^{-10}
Premature mortality		
PM2.5[b]	Based on 1 $\mu g/m^3$ increase in annual PM2.5 mean concentrations leading to a 0.4% increase in premature deaths (Pope et al. 2002)). The midpoint from methods of Crettaz et al. (2002) and Huijbregts et al. (2005).	1.4×10^{-5}

[a] Assuming 70 kg body weight and breathing rate of 20 m^3/d

[b] The PM2.5 EF reflects premature mortality, including cancer and other diseases.

3.3.2. Human Damage Factors (HDFs) for Cancer and Non-cancer Diseases

The combined effect factors (EF_x) for both cancer and non-cancer burden and the fate factor (FF_x) were combined to obtain human damage factors expressed as DALYs/kg(emitted) for each pollutant. These results are summarized in Table 11. These HDF values result from combining the cancer and non-cancer (Category 2) EF_x values given in Table 10 with the FF_x, according to Eq. 2. For the FF_x, the *iFi* values reported in Table 9 were converted to a population-based *iF*, based on the populations given in Table 2.

Table 11. Chemical-specific HDFs (DALYs/kg emitted) for cancer, non-cancer, and premature mortality health effects in the California population

	Urban Counties [a]	Rural—All Counties	Rural—Counties with Power Plants	South Coast Air Basin	San Francisco Bay Area Air Basin
Cancer					
Benzene	1.3×10^{-7}	9.8×10^{-9}	1.3×10^{-8}	1.3×10^{-7}	1.3×10^{-7}
BaP (ingestion and inhalation)	7.1×10^{-5}	4.7×10^{-6}	7.5×10^{-6}	8.1×10^{-5}	1.3×10^{-4}
BaP (inhalation only)	9.1×10^{-7}	6.2×10^{-8}	1.0×10^{-7}	1.0×10^{-6}	1.7×10^{-6}
Naphthalene	2.0×10^{-8}	1.4×10^{-9}	2.1×10^{-9}	2.2×10^{-8}	2.9×10^{-8}
Non-Cancer					
Benzene	1.1×10^{-7}	8.4×10^{-9}	1.1×10^{-8}	1.1×10^{-7}	1.1×10^{-7}
NO_x	3.6×10^{-7}	2.5×10^{-8}	3.5×10^{-8}	3.7×10^{-7}	5.0×10^{-7}
SO_2	2.2×10^{-8}	1.5×10^{-9}	2.2×10^{-9}	2.1×10^{-8}	2.6×10^{-8}
Premature Mortality					
PM2.5	4.6×10^{-5}	3.3×10^{-6}	4.9×10^{-6}	5.1×10^{-5}	6.8×10^{-5}

[a] Result is consistent whether or not the area and population of the region includes only counties with power plants or all urban counties.

Table 11 reveals a number of issues of interest. First, the HDF values are somewhat smaller than the researchers expected. But comparisons with the work of other researchers confirm that this range of values is consistent with their findings. The HDFs for different regions fall within one order of magnitude for the San Francisco Bay Area air basin, South Coast air basin, and generic urban regions. The latter two regions have the most similar HDFs for each chemical emitted. The largest HDF values tend to be in the SFBA air basin, particularly for the cancer HDFs. This is primarily due to the relatively higher population density than any other region. The rural regions tend to have HDF values one to two orders of magnitude lower per chemical than the HDFs in the SFBA air basin. The premature mortality HDF for PM2.5 is the highest among the HDFs considered for inhalation intake. In terms of the range of values due to uncertainty, non-cancer HDFs for NO_x and benzene are the same. In contrast, the HDF non-cancer values for SO_2 are an order of magnitude lower.

It should be recognized that the EF_x values as well as FF_x values have significant uncertainty and variability. The EF_x can range within an order of magnitude for each chemical (see Appendix B, Tables B-1a and 2b). This is not surprising, as others have found that EF_x-related data can be highly uncertain due to lack of knowledge and true variability in the population of exposed persons. Nishioka et al. (2002) reported that the "single most influential uncertainty is the uncertainty in the concentration-response function for premature mortality." However, it is beyond the scope of this study to determine whether this is the case here, in particular, to determine whether the emissions factor data are more uncertain than the premature mortality characterizations. They are both uncertain due to lack of true knowledge about their values. However, because multiple emissions factor data for certain fuel-technology power plants were available, this study was able to characterize a plausible range for the emissions estimates. In contrast, insufficient data from multiple studies were available to quantitatively characterize a range of plausible premature mortality values.

3.4. Estimates of Disease Burden Added or Averted: Residential Attic Insulation Case Study

The addition of residential fiberglass attic insulation is used as a case study to illustrate an application of the health benefits methodology presented here. There are two components. First, with the assumption that all electricity-heated homes in California are brought into compliance with DOE standards for attic insulation, energy savings over the assumed 50-year lifetime of the insulation are determined. These energy savings are then used to determine the resulting emissions and disease burden reductions in California. In the second component, the energy requirements, emissions, and disease burden from the manufacture of fiberglass insulation required to meet the energy savings goals are determined and compared to the disease burden reduction from the use of that insulation.

3.4.1. Energy Savings and Resulting Emissions and Disease Burden Reductions

Reduction in Energy Demand and Power Plant Emissions

Equation 12 in Section 2.5 was used to determine for each pollutant the amount (kg) of pollutant emissions reduction for each additional megatonne (Mt) of insulation used in California. Table 12 summarizes the statewide power plant emissions eliminated in urban and rural regions due to the installation of additional fiberglass residential installation across the state. Ranges are given, due to variability in the plant efficiencies as provided in Appendix A, Table A-1.

A number of issues arise from the results in Table 12. In both urban and rural regions, the emissions reduction for each pollutant ranges roughly by a factor of two, depending on the power plant efficiencies assumed in the estimates. Because value ranges for efficiencies of coal-powered cogeneration plants are not provided in the data compiled in Appendix A, the emissions eliminated in rural regions are point estimates (based on a coal plant efficiency of 0.4). As shown by Table 12, the savings from oil- and WTE-powered plants are at least two orders of magnitude greater in urban regions than in the rural regions. However, chemical emissions saved from natural gas-powered plants tend to be within the same order of magnitude in urban and rural regions. Exceptions to this are NO_x and SO_2 emissions savings, which tend to be more than an order of magnitude greater in urban regions. Savings of emissions from coal-fired plants (including petroleum coke and crude oil fuel) are within an order of magnitude for BaP, PM2.5, and SO_2, but are an order of magnitude greater in rural than urban regions for benzene, naphthalene, and NO_x emissions.

Table 12. Ranges[a] of total emission savings (kg) over 50-year assumed lifetime of fiberglass insulation (kg) in urban and rural regions

a) Urban

	Coal (kg)		Natural Gas (kg)		Oil (kg)		WTE (kg)	
	midpoint	range	midpoint	range	midpoint	Range	midpoint	range
BaP	1.43×10^{-1}	1.41×10^{-1} – 1.44×10^{-1}	7.7×10^{2}	5.7×10^{2} – $9.6 \times$	1.8×10^{4}	9.2×10^{3} – 2.6×10^{4}	n/a	n/a
Benzene	7.7×10^{2}	7.3×10^{2} – 8.1×10^{2}	7.4×10^{3}	5.2×10^{3} – $9.5 \times$	1.3×10^{4}	7.0×10^{3} – 1.9×10^{4}	2.5×10^{2}	1.4×10^{2} – 3.6×10^{2}
Naphtha-lene	7.7	7.3 – 8.1	1.1×10^{3}	7.5×10^{2} – $1.4 \times$	9.6×10^{3}	5.1×10^{3} – 1.4×10^{4}	n/a	n/a
NO_x	7.8×10^{6}	7.4×10^{6} – 8.2×10^{6}	2.1×10^{8}	1.4×10^{8} – $2.8 \times$	1.5×10^{8}	8.3×10^{7} – 2.2×10^{8}	2.0×10^{6}	1.1×10^{6} – 2.9×10^{6}
PM2.5	1.7×10^{6}	1.6×10^{6} – 1.8×10^{6}	1.7×10^{6}	1.3×10^{6} – $2.1\times$	2.3×10^{6}	1.3×10^{6} – 3.2×10^{6}	n/a	n/a
SO_2	1.15×10^{7}	1.1×10^{7} – 1.2×10^{7}	2.0×10^{6}	1.4×10^{6} – $2.5\times$	7.9×10^{7}	4.7×10^{7} – 1.1×10^{8}	5.5×10^{5}	3.1×10^{5} – 7.8×10^{5}

b) Rural

	Coal[b] (kg)	**Natural Gas (kg)**		**Oil (kg)**		**WTE (kg)**	
		midpoint	range	midpoint	Range	midpoint	range
BaP	1.3×10^{-1}	2.9×10^{2}	2.1×10^{2} – 3.7×10^{2}	6.9×10^{1}	3.7×10^{1} – 1.0×10^{2}	n/a	n/a
Benzene	4.3×10^{3}	1.8×10^{3}	1.3×10^{3} – 2.3×10^{3}	9.6×10^{1}	5.1×10^{1} – 1.4×10^{2}	1.1	8.7×10^{-1} – 1.3
Naphthalene	4.3×10^{1}	2.3×10^{2}	1.6×10^{2} – 3.0×10^{2}	6.4×10^{1}	3.4×10^{1} – 9.4×10^{1}	n/a	n/a
NO_x	4.6×10^{7}	4.1×10^{7}	2.8×10^{7} – 5.4×10^{7}	1.0×10^{6}	5.5×10^{5} – 1.5×10^{6}	7.1×10^{3}	5.8×10^{3} – 8.4×10^{3}
PM2.5	9.4×10^{6}	8.6×10^{5}	6.2×10^{5} – 1.1×10^{6}	1.5×10^{4}	8.5×10^{3} – 2.2×10^{4}	n/a	n/a
SO_2	6.3×10^{7}	5.1×10^{5}	3.6×10^{5} – 6.5×10^{5}	5.0×10^{5}	2.9×10^{5} – 7.1×10^{5}	2.3×10^{3}	1.9×10^{3} – 2.7×10^{3}

[a] Ranges are based on variable data on fuel-technology efficiencies.

[b] Includes the Mohave electricity generating plant in Clarke County, Nevada, located on the border with California. Because only one efficiency is used (0.4), no range is reported.

The emissions reductions in Table 12 correspond to energy savings of approximately 4.7×10^{8} MWe-h (1.7×10^{18} J) over the assumed 50-year lifetime of the insulation. The savings from the different energy technologies over this 50-year period are approximately:

- 2.6×10^7 MWe-h (9.2×10^{16} J) from coal
- 3.8×10^8 MWe-h (1.4×10^{18} J) from natural gas
- 6.3×10^7 MWe-h (2.3×10^{17} J) from oil
- 2.4×10^6 MWe-h (8.7×10^{15} J) from WTE technologies

These savings are not dependent on the plant efficiency assumed, but depend on the current MWe output (Energy Commission 2004) of the fuel-technology power combination in the given region.

These results are consistent with those presented by Levy et al. (2003). They estimate that adding insulation to existing single-family homes throughout the U.S. to meet the International Energy Conservation Code (IECC 2000, published by the International Code Council, 1999) would save approximately 280 TBtu/y (3.0×10^{17} J/y) in all-electric-heated homes of primary energy (primarily in the southern region). For the western U.S. (Pacific and Mountain) region, the source savings is approximately 41 TBtu/y, or 4.3×10^{16} J/y (Levy et al. 2003). By the methods of the current study, California is estimated to save nearly 3.4×10^{16} J/y if insulation was upgraded to DOE-recommended levels in homes heated with electricity.

Levy et al. (2003) also estimate that the energy savings from added insulation eliminates approximately 3,100 tonnes (t) of PM2.5, 190,000 t of SO_2, and 100,000 t of NO_x per year over the entire contiguous US. In the western US, they estimate that the quantity of these pollutants eliminated by insulation in homes heated with electricity is approximately 210 t of PM2.5, 8300 t of SO_2, and 7500 t of NO_x per year. The current study estimates that approximately 318 t of PM2.5, 3600 t of SO_2, and 11,900 t of NO_x are eliminated in California per year, assuming homes heated by electrical energy install DOE-recommended levels of fiberglass attic insulation.

The higher NO_x and PM2.5 savings found in this study most likely reflect methodological differences in assessing the housing stock requiring additional insulation and in characterizing the power plant emissions. For example, Levy et al. (2003) assume 63% of single-family homes in each state had "adequate or poor insulation" and required additional insulation to meet the International Energy Conservation Code (IECC) 2000 levels, which to the authors' knowledge are not as stringent as the DOE levels. In contrast, this study's approach was based on using information about existing electricity-heated single-family homes (distributions of housing characteristics based on housing vintage) and bringing them up to DOE-recommended insulation levels. Because of the vintage analysis, this study found that over 60% of the energy savings and resulting emissions reductions were due to the installation of additional fiberglass insulation to meet the DOE-recommended insulation requirements, Rrec, (DOE 2002) in homes built before 1978.

Additionally, Levy et al. (2003) relied solely on the eGRID to estimate emissions of NO_x, PM2.5, and SO_2, and their emissions assumptions resulted in "lower emission rates than a capacity-based allocation," such as was used in this study. However, because of fewer coal-fired power plants in California, this study estimates lower avoided levels of SO_2, in comparison with the Levy et al. (2003) analysis of the western US.

Reduction in Disease Burden

The next element of this study was to determine the health benefits of insulation on a functional unit basis. The functional unit selected is the mass (million metric tonnes, or Mt) of insulation used. Table 13 presents this study's estimates of DALYs saved (over an assumed insulation lifetime of 50 years) per Mt of insulation installed. Based on the minimum and maximum emissions given in Table 12 and the uncertainty in the power plant efficiencies, the values in Table 13 provide the midpoint of the value range of DALYs saved per Mt of insulation installed. The resulting DALYs saved are between 914–1170 DALYs/Mt insulation over the entire 50-year assumed lifetime of the installed insulation. Due to inhalation intake, the best estimate of the DALYs saved per Mt insulation installed is 1043 DALYs (the sum of the values in the last row of Table 13). This is mostly attributable to elimination of PM2.5 emissions. Because the total insulation required to meet DOE guidelines is approximately 1.1 Mt, up to 1147 DALYs could be averted.

Table 13. DALYs saved per Mt insulation installed. Values shown represent the midpoint of the value range based on the range of emissions given in Table 12.

	Natural Gas		**Coal**		**Oil**		**WTE**	
	Urban, all counties	Rural, all counties	Urban, all counties	Rural, counties with power plants	Urban, all counties	Rural, all counties	Urban, all counties	Rural, all counties
Carcinogens								
Benzene	9.5×10^{-4}	2.2×10^{-4}	1.0×10^{-4}	7.0×10^{-4}	1.7×10^{-3}	1.2×10^{-5}	3.2×10^{-5}	1.3×10^{-7}
BaP-ingestion and inhalation	5.2×10^{-2}	1.8×10^{-2}	9.7×10^{-6}	1.2×10^{-5}	1.2	4.2×10^{-3}	n/a	n/a
BaP-inhalation only	6.7×10^{-4}	2.3×10^{-4}	1.3×10^{-7}	5.5×10^{-3}	1.5×10^{-2}	5.6×10^{-5}	n/a	n/a
Naphthalene	3.3×10^{-2}	4.2×10^{-6}	1.5×10^{-7}	1.2×10^{-6}	1.8×10^{-4}	1.2×10^{-6}	n/a	n/a
Non-carcinogens								
Benzene	8.4×10^{-5}	1.9×10^{-4}	8.5×10^{-5}	6.0×10^{-4}	1.9×10^{-3}	1.0×10^{-5}	2.7×10^{-5}	1.1×10^{-7}
NO_x	73	13	2.7	21	52	3.3×10^{-1}	6.9×10^{-1}	2.3×10^{-3}
SO_2	4.1×10^{-2}	1.0×10^{-2}	2.3×10^{-1}	1.8	1.7	9.8×10^{-3}	1.1×10^{-2}	4.5×10^{-5}
Premature Mortality								
PM2.5	75	37	75	588	100	6.4×10^{-1}	n/a	n/a
Total DALYs (inhalation) per Mt insulation installed	148	50	78	611	154	1.0	7.0×10^{-2}	2.3×10^{-3}

Because the results in Table 13 are the first attempt at characterizing the hazardous air pollutant (benzene, benzo(a)pyrene, and naphthalene) DALYs saved from adding residential insulation, comparisons with other studies are not possible. It is possible, however, to compare the premature deaths eliminated due to the elimination of NO_x, SO_2, and PM2.5 emissions from power plants attributable to the 1.1 Mt of insulation installed in California. Based on a published burden of disease analysis (Lvovsky 2001), approximately 10 DALYs are equivalent to 1 premature death in adults (older than 40 years of age). Thus, the results of this study indicate that approximately 115 premature deaths are averted, or 2.3 deaths per year over 50 years, due to installation of residential attic insulation in California. Approximately 20 premature deaths are attributable to reductions in NO_x and approximately 96 are due to reductions in PM2.5. As Table 13 displays, the most significant contribution to these health benefits is due to emissions averted from coal-powered generating plants located in rural counties (primarily the Mohave coal power plant). By comparison, Levy et al. (2003), estimate that 7 premature deaths per year are averted in the western region of the U.S. because of emissions reductions in PM2.5, SO_2, and NO_x, due to the upgrading of existing insulation in electricity-heated single-family homes to levels recommended in the IECC 2000.

3.4.2. Emissions and Energy Analysis for Fiberglass Insulation Manufacturing

In order to address the net health benefits of end-use energy efficiency, the disease burden associated with the manufacture of the fiberglass insulation was determined. This study considered both the emissions from the energy required to manufacture the insulation as well as the direct emissions from the insulation manufacturing process.

The electrical energy used to manufacture 1.1 Mt of insulation (the amount required to bring California's electrically heated single-family homes up to DOE insulation standards) is approximately 3.1×10^{10} MJ (based on an estimate of 27.9 MJ/kg for the embodied energy of fiberglass materials reported by Franklin Associates (1991). Because this amount is two orders of magnitude less than the 1.7×10^{12} MJ of electrical energy saved over the 50-year assumed lifetime of the insulation, it was not necessary to carry out an explicit analysis of the emissions added by electrical energy to produce insulation.

In calculating emissions from insulation manufacturing, there is significant uncertainty due to lack of information about emissions from fiberglass manufacturing. Emissions factors used in the NO_x and SO_2 estimates are required on material-manufactured basis, but they are reported on a material-processed basis in the AP 42 (EPA 1985). *Material manufactured* refers to the amount of final product (insulation) produced. *Material processed* refers to the amount of raw material (silica-based glass) consumed in the production of final product (fiberglass insulation). For the purposes of this screening-level study, material manufacture and material processed were assumed to be equivalent.

For NO_x, the following manufacturing processes shown in Figure 5 have EFs available: glass melting (wool and textile) and oven curing. However, for SO_2, emission factors are available for only glass melting (wool and textile) processes. These emission factors are incorporated into the emissions estimates. For the other processes outlined in Figure 5, the AP 42 database provides no EF data for NO_x and SO_2. Additionally, because there are almost no published emissions factors for PM2.5 from glass-fiber manufacturing, AP 42 emission factors based on organic condensable PM emissions collected at the impinger portion of a PM sampling train were applied (EPA 1995–2000, Table 11.13.1). However, for processes shown in Figure 5, with the exception of rotary spin wool glass manufacturing (SCC 3-05-012-04), the AP 42 reports "no data" for emissions of organic condensable PM. Therefore, this report uses the midpoint of the R-19 and R-11 rotary spin wool glass manufacturing emission factors (3.7 kg organic condensable PM per tonne material processed) to estimate PM2.5 emissions from fiberglass manufacturing.

In spite of the large uncertainties, preliminary estimates of emissions were obtained and compared to results from similar studies. This study assumed that emissions associated with fiberglass manufacturing were not limited to California, but were instead assigned to a generic "urban" region of the US. Table 14 provides the estimated $\text{emissions}_{\text{fiberglass},i}$ from manufacturing the residential attic insulation and compares them to estimates of emissions saved from the equivalent reduction in power plant operations in California. As seen from Table 14, the California-specific emissions eliminated are an order of magnitude greater for PM2.5 and two orders of magnitude greater for NO_x and SO_2 than the estimated emissions from fiberglass manufacturing.

Table 14. Estimated emissions from manufacturing 1.1 Mt of residential attic insulation compared to emissions eliminated by reduced electricity production over 50 years

	Estimated $\text{Emissions}_{\text{fiberglass},i}$ (kg)	Total emissions (kg) eliminated in CA [a]
NO_x	5.8×10^6 [b]	$3.1 \times 10^8 – 6.1 \times 10^8$
PM2.5	5.9×10^6 [c]	$1.4 \times 10^7 – 1.8 \times 10^7$
SO_2	5.1×10^6 [b]	$1.2 \times 10^8 – 1.9 \times 10^8$

[a] Based on urban and rural emissions ranges given in Table 12 (a and b).

[b] EFs given per tonne material processed, and it is assumed that these apply to the tonne of finished product.

[c] PM2.5 emissions are estimated from the organic condensable PM10 (i.e., that collected in the impinger portion of a PM sampling train), and these EFs are reported for rotary spin wool glass manufacturing.

To determine the size of the population exposed to the fiberglass emissions and the *iFi* for this population, this study assumed that all the fiberglass was manufactured in the contiguous U.S. and assigned the exposure to a generic U.S. region. The DALYs associated with pollutant emissions for each Mt of insulation manufactured were calculated based on Equation 2. Table 10 provides the EF_x used for NO_x, PM2.5, and SO_2 emissions from fiberglass manufacturing (the EF_x depends only on the pollutant, not upon the source of the pollutant). For the fate factor FFx, i.e., the population-based iF, a typical *iFi* of 10^{-13} was used. To determine the population to which this *iFi* applies, the characteristic travel distance (CTD, km) of each pollutant was determined. The CTD is the radial distance from the source where the concentration of a chemical falls to 1/e (37%) of the concentration at the source (Bennett et al. 1998) and can be used to characterize the area with an exposed population. The formulation for the CTD is

$$CTD = u/k_{eff} \qquad \textit{(Eq. 14)}$$

where:

u is the long-term average wind speed (m/s).

k_{eff} is the effective reaction rate of a pollutant (per second) in the environment.

The k_{eff} term takes into consideration partitioning and degradation of a chemical in multiple media and can be estimated with models such as CalTOX.

There are no published estimates of k_{eff} for PM2.5. But BaP is strongly particle associated. So the CTD of BaP was used as a proxy for the PM2.5 CTD, which is estimated at 30 km. For NO_x and SO_2, which partition completely to air and undergo irreversible deposition, the CTD is simply the ratio of long-term average wind speed and reaction/deposition rates. In much of the US, long-term average wind speed is on the order of 3–4 m/s or about 300 km/d. Removal by deposition reaction for these substances is about 3 moles/d, so for both NO_x and SO_2, the CTD is assumed to be on the order of 100 km.

The area (πr^2) corresponding with each of these CTDs was converted to an exposed population by using an assumed population density of 27.2 persons/km^2, which is the average for the entire U.S. (U.S. Census Bureau 1990). Table 15 summarizes the CTD, the area, the population size, and the resulting DALYs/Mt of insulation manufactured based on the emissions estimates from fiberglass manufacturing.

Table 15. Summary of the characteristic travel distance (CTD), area, population size and DALYs/Mt insulation manufactured

	CTD (km)	Area (km^2)	Population size [a]	DALYs/Mt manufactured
PM2.5	30 [b]	2,826	76,867	5.6×10^{-1}
NO_x	100 [c]	31,400	850,000	4.3×10^{-2}
SO_2	100 [c]	31,400	850,000	1.2×10^{-3}

[a] Assuming a population density of 27.2 persons/km^2 (U.S. Census Bureau 1990)

[b] Assuming a CTD of BaP

[c] Realistic estimate of an exposure radius

The DALYs/Mt of insulation resulting from the manufacturing process as given in Table 15 are substantially lower (by four orders of magnitude) than the DALYs/Mt saved over 50 years from reduced power plant emissions attributable to this quantity of insulation. Although there are uncertainties in both the emissions and exposure calculations for the manufacturing of fiberglass insulation, these numbers indicate that there is a likely net health benefit associated with the expanded use of fiberglass insulation. Much of the uncertainty in the estimate of net health benefit is due to the large uncertainty about the emission factors from fiberglass manufacturing.

Others have also observed a net health benefit from the use of fiberglass insulation. In considering the premature mortality attributable to PM2.5 exposures, Nishioka et al. (2005) reported that adding insulation to new homes in the U.S. averts 60 premature deaths, or 1.2 premature deaths per year, over a 50-year period, due to reduced energy consumption. In the Nishioka study, the primary health burden associated with supplying this insulation (approximately 0.3 Mt of insulation) was associated with PM2.5 emissions from the manufacturing of fiberglass (mineral wool). All supply-chain processes resulted in a one-time health burden of approximately 14 premature deaths for one year of increased output (Nishioka et al. 2005).

The Nishioka study included residential combustion as well as power plant emissions. In future studies incorporating the TRACI-CalTOX LCIA system, the inclusion of other home heating technologies besides electricity, such as wood combustion and natural gas heating, would quantify additional health benefits such as those found by Nishioka et al. (2005).

4.0 Conclusions and Recommendations

The authors' conclusions and recommendations are presented here in the context of the objectives that were set for this definition study:

- To provide a roadmap to organize a health benefits study for energy efficiency.
- To demonstrate the use of life-cycle impact assessment (LCIA) tools such as the U.S. Environmental Protection Agency (EPA) TRACI-CalTOX system (Bare et al. 2002) to fill in this roadmap.
- To provide an informative case study to illustrate how one can construct and evaluate a health benefits study for energy-efficiency improvements in California.

To meet these project objectives, the research team employed standard LCIA methods that have been developed for evaluating and allocating the health and environmental impacts of energy technologies.

4.1. Conclusions

4.1.1. Providing a Roadmap to Organize a Health Benefits Study for Energy Efficiency

This study was successful in organizing the roadmap, data, and computational tools needed to assess both disease burden and health benefits from changes in energy production and consumption in California. The framing of this problem produced a repository of important information that will be useful for future comparative studies. Among the information that has been gathered are (1) a compilation of power plants that produce power for California along with their location and region, fuel technology, and relative contribution to power consumption; (2) emissions factors for a portfolio of energy production technologies used in California; (3) location-specific emissions/exposure relationships (fate factors); and (4) a pollutant-specific set of human damage factors for power plants in California.

Using this roadmap, the study characterized the current levels of atmospheric emissions and resulting health burden from six pollutants that are potential human health hazards. The magnitude and location of atmospheric emissions of NO_x, SO_2, PM2.5, benzo(a)pyrene, benzene, and naphthalene were estimated for coal, natural gas, oil, and waste-to-energy power plants in California, as well as the Mohave coal plant on the Nevada border.

Based on this portfolio of power generation technologies, emissions rates per unit (MWe-y) of electricity production were quantified for urban and rural regions of California, as well as for the San Francisco Bay Area and South Coast air basins. Based on these emissions, chemical-specific disease burdens were determined and compared with those averted through the introduction of an energy-efficient technology (fiberglass attic insulation). To make possible these characterizations and comparisons, relevant models and data were selected for defining the boundaries of the analysis, estimating and locating emissions, and quantifying disease burdens.

4.1.2. Demonstrating the Use of Life-Cycle Impact Assessment Tools to Fill in This Roadmap

The researchers demonstrated the use of LCIA tools such as the TRACI-CalTOX approach to determine how atmospheric emissions from power plants distribute in the environment and what populations are impacted. Instead of a site-specific assessment, this study allocated emissions to generic urban or rural regions. Urban and rural exposure factors (emission-to-intake factors) were characterized, in addition to those for the San Francisco Bay Area and South Coast air basins. The source-to-dose relationships for each of these regions were quantified based on the environmental dispersion, fate, exposure, and subsequent intake of the airborne chemicals using the multimedia modeling framework of CalTOX. The archetypal individual intake fraction, *iFi*, for urban exposures tended to be slightly greater than the rural exposure factors. The *iFi*s estimated for the South Coast air basin also tracked the generic urban *iFi* levels while the SFBA air basin *iFi*s tended to be roughly an order of magnitude greater. The use of the CalTOX model with its ability to provide probabilistic results makes possible a process for addressing uncertainty and variability in future assessments.

Based on CalTOX, the typical (midpoint) *iFi* levels for urban and rural regions were converted to potential toxic effects through the human damage factor (HDF) metric. The HDF characterizes the population health burden, in units of disability-adjusted life years (DALYs) per kg pollutant emitted. This study finds that inhalation HDFs resulting from power plants in California are dominated by PM2.5 exposures. The PM2.5 inhalation HDFs are at least two orders of magnitude greater than the inhalation HDFs of the other chemicals.

Overall, this study was successful in demonstrating the use of the LCIA framework in assessing pollutant emissions from California power plants and the associated non-cancer and cancer disease burdens. A particularly important finding was that even this extremely coarse level of spatial detail within the TRACI-CalTOX system can provide valuable screening-level information because of its inherently regional multimedia modeling framework. Suggested improvements to the TRACI-CalTOX system are described in Section 4.2.

4.1.3. Providing an Informative Case Study to Illustrate How One Can Construct and Evaluate a Health Benefits Study for Energy Efficiency Improvements in California

The research team was able to construct a case study on the disease burdens averted due to the installation of approximately 1.1 million metric tons (Mt) of additional fiberglass attic insulation to reach DOE-recommended levels in California single-family residences heated by electricity. Based on a 50-year assumed lifetime of the installed insulation, the avoided disease burden is approximately 1000 DALYs from power plant emissions per Mt of insulation installed, mostly from the elimination of PM2.5 emissions. In terms of premature deaths averted, these DALYs translate to approximately 120 premature deaths averted. Approximately 20 premature deaths are attributable to reductions in NO_x and approximately 100 are due to emissions reductions of PM2.5. When compared with the disease burden associated with the manufacture of this additional insulation within the LCIA framework, this study concludes that the DALYs saved per Mt insulation installed are nearly four orders of magnitude greater than those associated with the insulation's manufacture.

The case study reveals that there is a disease burden associated with electricity generation in California through application of an LCIA framework for impact assessment. This is due in large part to emissions of NO_x and PM2.5 from coal-, oil-, and natural gas–fueled power plants. Although existing methods for fiberglass manufacturing are quite high in particulate matter generation, these methods still yield PM2.5 emissions far below those estimated in this report to be averted due to the installation of fiberglass insulation in existing homes in California to meet current DOE levels.

4.2. Recommendations for Further Study

The demonstrated utility of an LCIA framework—namely TRACI-CalTOX—for this study supports the need to evaluate the utility of LCIA for other comparative health benefits studies. For example, this approach could be used to assess the health benefits of fuel efficiency in the transportation sector. There is new and ongoing research in the epidemiology field indicating a significant disease burden for populations living near major roadways (Jerrett, 2005). The framework used in this study provides methods for allocating disease burden in different geographic regions. This approach would likely be informative in transportation energy use planning. The framework used here could be adapted to transportation through a one-year study that focuses on populations living near roadways. The estimated cost for this type of study is $100K to $200K.

The successful application of LCIA methods reveals the value of exploring how this approach could be applied to life-cycle studies of other energy production and energy efficiency technologies. Because the models and data used in this study were developed for generic applications in life-cycle impact assessment, there is a need for research to expand, test, and support extensions of this exploratory study to other comparative energy assessments in California. This would be an ongoing support activity that could last for multiple years and would require financial support at a level of $100K per year.

Estimates of PM2.5 emissions and disease burden resulting from the manufacture of fiberglass insulation are so limited by uncertainty that a formal uncertainty analysis is needed to confirm conclusions about net health benefits of using fiberglass insulation. Also, there is a need to consider a broader range of pollutant emissions to assure that the PM2.5 is indeed the dominant contributor to the disease burden. A formal treatment of uncertainty and variability using Monte Carlo methods could establish confidence bounds around any comparative assessment. A probabilistic analysis using the existing framework would take from one to two years and cost from $100K to $200K.

Because PM2.5 (primary fine particulate matter) dominates the potential health savings from the reduction in power plant emissions, the researchers suggest that, in addition to the recommended uncertainty analysis, priority should be given to investigating the health benefits resulting from reductions in secondary particulate matter such as secondary aerosols and ozone. Research along these lines would provide much-needed supplementary information to this exploratory study.

To summarize, the researchers provide the following list of potential future comparative assessment opportunities using an LCIA framework:

- Extending the use of the LCIA framework in this report to evaluate the health benefits due to increased end-use efficiencies and corresponding reductions of additional pollutants, such as additional PAHs, metals, ambient mercury, secondary air pollutants (NO_x-ozone and NO_x-nitrate and SO_2-sulfate), and greenhouse gases.
- Extending this work to the health benefits associated with decreased residential combustion heating in addition to electrical end-use efficiency associated with additional fiberglass insulation.
- Including morbidity in the calculation of disease burden for the general population and also for susceptible populations due to PM2.5 exposures. (This study calculated only premature mortality, not morbidity, due to PM2.5).
- Extending this work to include health benefits to various sensitive subpopulations (in-utero, infants, elderly, asthmatics) due to reduced pollutant emissions.
- Considering how marginal energy use in California influences emissions reductions from energy-efficient end-use technologies.
- Considering the economic and social costs associated with increasing deployment of efficient end-use electric technologies.
- Considering the temporal potency of chemical exposure and finer spatial differences in exposure and associated health benefits.
- Comparing traditional health risk assessment methods, such as using the RfD to assess non-cancer health effects, with estimates of the effect factor based on an ED10.
- Exploring the sources of variability and uncertainty in the input parameters for an LCIA and conducting a systematic analysis of uncertainty in the CalTOX model structure and application that would differentiate and characterize between Type A uncertainty (true variability or randomness) or Type B uncertainty (true variability or randomness versus lack of knowledge).
- Incorporating the LCIA methods demonstrated in this report into a full life-cycle analysis of electricity production (including primary fuel extraction and transport) and fiberglass manufacturing.

4.3. Benefits to California

By including energy efficiency in comparative assessments for the current mix of energy technologies, the results and, in particular, the methods and data of this study provide key benefits to energy planning for California:

- A method for more-informed decision making, based on the ability to aggregate and systematically evaluate information on environmental implications of alternative energy systems in the context of energy efficiency choices.
- An example of how this method could be used to make decisions about improvement options for environmental quality, by identifying optimal areas for reducing emissions and effluents on the basis of a comparative assessment of population disease burden associated with alternative supply and end-use management options.
- An example of a more systematic approach for considering potential environmental and human health effects within the broader decision-making process.

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6.0 Glossary and List of Acronyms

ALC	absolute lymphocyte count
BaP	benzo(a)pyrene
BMD	benchmark dose
BW	body weight (kg)
BR	breathing rate (m^3/d)
Btu	British thermal units
CalTOX	a multimedia, multi-pathway fate and exposure model developed by UC Berkeley
CF_oral (rat →human)	oral ingestion conversion factor from rat to humans
CF_oral (mouse → human)	oral ingestion conversion factor from mouse to human
$CF_{Btu \rightarrow MWe}$	conversion factor from Btu to MWe-y (3.345×10^{-11} MWe-y per Btu)
CFx	characterization factor
CHP	combined heat and power
Cogen	cogeneration plant
CTD	characteristic travel distance (km)
D_{air}	diffusion coefficient in air
D_{water}	diffusion coefficient in water
DALY	disability-adjusted life year
$DALY_p$	the sum of years of life lost due to death and disability from the cancer caused by x (years lost/incidence)
DEER	Database for Energy Efficiency Resources (Energy Commission 2001)

DOE	U.S. Department of Energy
$ED50_{x,r}$	the lifetime dose [kg] of chemical *x* from exposure route *r* affecting 50% of the exposed human population. *$ED50_{x,r}$* can be estimated using the $TD50_{x,a}$ from animal experiments
EF	emission factor
$EF_{fiberglass,i}$	emission factor of pollutant, i, from the manufacture of fiberglass [kg pollutant/tonne insulation, finished product]
EF_x	effect factor [statistical years of life lost per mg intake of chemical x]
eGRID	Emissions and Generating Resource Integrated Database, developed by U.S. EPA
EIA	U.S. Energy Information Agency
EOR	enhanced oil recovery
EPA	U.S. Environmental Protection Agency
ESP	electrostatic precipitator
FF_x	fate factor, or the population intake of chemical *x* per unit of emission of chemical *x* [kg(intake)/y per kg(emission)/y]
gal	gallon
GW	gigawatt
HDD	annual heating degree days [^{o}F-d]
HDF	human damage factor
HHV	higher heating value of fuel
HV	heating value of fuel
HVAC	heating, ventilation and air conditioning
IAEA	International Atomic Energy Agency
IC	internal combustion

IECC	International Energy Conservation Code
iFi	individual intake fraction
J	Joule
$K_{d\_d/q/s/v}$	soil-water partition coefficient in sediment (d)/aquifer (q)/ground-soil (s)/vadose-zone soil (v) layer
kg	kilogram
K_{ow}	octanol-water partition coefficient
LCA	life-cycle assessment or analysis
LCIA	life-cycle impact assessment
LHV	lower heating value of fuel
LOEL	lowest-observed effect level
MDL	method detection limit
MMBtu	million Btu
Mt	million metric tonnes
MWe	megawatt electric
MWt	thermal megawatt
NOEL	no-observed effect level
NO_x	oxides of nitrogen (principally nitrous oxide and nitrogen dioxide)
NSPS	New Source Performance Standards
PC	pulverized coal
PM2.5	particulate matter with aerodynamic diameter less than 2.5 μm
P_{vap}	vapor pressure (Pa)

q_1^*	the 95th% upper confidence bound on the linearized multistage model slope factor q_1
$R_{baseline}$	the baseline R-values for homes heated with electricity reported in the 2001 DEER study
R_{rec}	additional attic insulation needed to reach the latest DOE recommended insulation requirements
RfD	U.S. EPA reference dose [mg/kg-BW/d]
$S_{bituminous}$	sulfur content of bituminous coal
scf	standard cubic feet
S_{diesel}	sulfur content of diesel fuel
$S_{distillate}$	sulfur content of distillate oil
SFBA	San Francisco Bay Area
SO_2	sulfur dioxide
$S_{subbituminous}$	sulfur content of subbituminous coal
S_{water}	solubility in water
TAPs	toxic air pollutants
TD50	daily dose rate [mg/kg(BW)-d] that induces tumors in half of the test animals that would have otherwise been tumor free at no dose
$t_{insulation}$	lifetime of the fiberglass insulation [y]
TRACI	Tool for the Reduction and Assessment of Chemicals and other environmental Impacts, developed by U.S. EPA
TU	toxic unit
$V_{insulation}$	volume of installed insulation
WTE	waste to energy
y	year

α	parameter (in addition to β) used to define the scaling in the beta distribution
β	parameter (in addition to α) used to define the scaling in the beta distribution
$\beta_{ED10\text{-}x}$	the linear low dose response slope factor [individual lifetime risk of cancer per (mg/kg BW-day) intake] for chemical x, inducing a response over background of 10% for humans
ηe	electrical efficiency [-]
$p(d \mid \Delta TU$	the probability of occurrence of a disease, d, caused by a marginal change in the ambient toxic unit (TU) [-]
$\rho_{fiberglass}$	density of fiberglass (9 kg/m^3)

Appendix A

Tables of Data Used to Estimate Pollutant Emissions per MWe-y

Appendix A: Tables of Data Used to Estimate Pollutant Emissions per MWe-y

Table A-1: Ranges of electrical efficiencies (η_e) of power plants, by fuel and technology type. These ranges were used to define beta distributions (with α=2; β=2) to estimate emissions.

Primary fuel	Simple cycle	CHP/cogen/ Combined cycle
Coal	0.33-0.39 [a]	0.4 [b]
Natural gas		
Gas turbine	0.15-0.42 [c]	0.58-0.84 [d]
Steam turbine or boiler	0.10-0.35(<250 MW)[e] 0.25-0.45(>250 MW)[f]	n/a [g]
IC or reciprocating engine [h]	0.25-0.50 [i]	0.70-0.80 [j]
Oil[k]		
gas turbine	0.15-0.42 [c]	0.58-0.84 [d]
Steam turbine or boiler	0.10-0.35(<250 MW) [e] 0.25-0.45(>250 MW) [f]	n/a [g]
IC or reciprocating engine [h]	0.30-0.50 [m]	n/a [n]
WTE [o]		
gas turbine	0.15-0.42 [c]	0.58-0.84 [d]
steam turbine or boiler	0.10-0.35(<250 MW)[e] 0.25-0.45(>250 MW)[f]	n/a [g]
IC or reciprocating engine [h]	0.25-0.50 [i]	0.70-0.80 [j]

n/a: not applicable

[a] Minimum efficiency reported in EPA (2001) as 0.33-0.34 of subcritical systems, with a maximum of 5% higher efficiency with specific improvements (listed in Table 2 of EPA, 2001).

[b] Maximum efficiency reported in coal fired power plants (Polk Power Plant) with integrated gasification combined cycle (EPA, 2001).

[c] Range of simple cycle η_e given by AP42 (EPA, 1995-2000). Values from other references for η_e are within this range (Khrushch, et al, 1999; EIA, 2000; Gulf Coast, 2005).

[d] Range of combined cycle, or cogeneration, η_es reported. Minimum and maximum are reported here (Khrushch, et al., 1999 and AP42, EPA, 1995-2000, respectively). Values from EIA (2000) and Gulf Coast (2005) fall within this range.

[e] Range of smaller steam turbines used at smaller plants which make electricity as a byproduct of delivering steam to processed or district heating systems, and smaller steam turbines used in industry or backpressure (non-condensing) turbines (EIA, 2000 and Gulf Coast, 2005). Assume these are plants with < 250MWe output.

[f] Range of upper end steam (condensing) turbines designed for large electric utility plants(EIA, 2000 and Gulf Coast, 2005) . Assume these are plants with > 250MWe output.

[g] Assumes that CHP/cogeneration/combined cycle refers primarily to gas turbines with steam turbines, not vice versa. If a steam turbine or boiler was reported as a cogeneration facility, assume it is a gas turbine with CHP/cogen/combined cycle technology and the associated η_e value.

[h] Reported as η_e for reciprocating engines (spark ignition uses natural gas as preferred fuel and compression ignition uses diesel or other heavy fuel). Assume that these η_es apply to the plants, which report internal combustion (IC) engines as technology to generate electricity, because, like rotary engines, reciprocating engines are another class of IC engines.

[i] Range of natural gas fired spark ignition engine (EIA, 2000 and Gulf Coast, 2005). Low end applies to smaller stoichiometric engines, which require 3-way catalyst after treatment, and high end refers to lean burn natural gas engines.

[j] Range of natural gas fired reciprocating engine operating in CHP mode (Gulf Coast, 2005).

[k] Applies to both distillate and diesel fueled plants.

[m] Range of diesel fueled compression engine η_e s (EIA, 2000 and Gulf Coast, 2005).

[n] η_e s were not located. No plants in the Energy Commission database (Energy Commission, 2004) list cogeneration together with reciprocating engine technologies fueled by oil (either diesel or distillate oil).

[o] Natural gas, methane, digester or landfill gas. For those plants that are reported as having brownfield or greenfield technologies (all happen to be 'peakers' i.e., constructed to supply peak electricity demand), assume the simple cycle gas turbine plant η_es apply (the individual web sites of the plants support this assumption).

Table A-2(a-f): Chemical emission factors used to estimate emissions from electricity generation from California power plants.

A-2a) Emission factors for SO2 emissions

Primary Fuel	Technology	Emission Factor		
		Value	**Units**	**Rating**
Coal	Bottoming cycle, topping cycle, steam turbine, fluidized boiler, or not reported			
Bituminous		38 x $S_{bituminous}$ (=19.0) [a,b]	lb/ton	A or B
Subbituminous		35 x $S_{subbituminous}$ (=17.5) [a,c]	lb/ton	A or B
Oil				
Distillate	Combustion or gas turbine	28.3[f]	lb/1000 gal oil	B
	Steam turbine			
	MW > 30	157 x $S_{distillate}$ (= 31.4) [e]		A
	MW < 30	142 x $S_{distillate}$ (= 28.4) [e]		A
Diesel		142 x S_{diesel} (=56.8) [d]	lb/1000 gal oil	A
Natural Gas	Combustion or gas turbine	3.5[h]	lb/10^6 scf	B
	Steam turbine	0.6[g]	lb/10^6 scf	A
	Reciprocating engine	0.62[g,j]	lb/10^6 scf	A
WTE				
Digester gas	Gas turbine, combined cycle, or internal combustion	3.9[i]	lb/10^6 scf	D
Landfill gas	Brownfield, greenfield, active flare/LFGTE, gas turbine, steam turbine, methane gas, internal combustion, or reciprocating engines.	1.8[i]	lb/10^6 scf	C

[a] It is assumed that the sulfur content of bituminous coal ($S_{bituminous}$) and subbituminous ($S_{subbituminous}$) is 0.5% (EIA, 2002), expressed as 0.5.

[b] Expressed as SO_2, SO_3 and gaseous sulfates. On average, 95% of fuel sulfur in bituminous coal is emitted as SO_2, and only 0.7% as SO_3 and gaseous sulfate. Value reported is the same for all firing configurations reported, including PC dry-bottom wall-fired firing configurations (pre-NSPS, pre-NSPS with low-NOx burner, and NSPS); PC dry bottom cell burner fired configurations; PC dry bottom tangentially fired (pre-

NSPS, pre-NSPS with low-NOx burner, and NSPS); PC wet-bottom wall-fired (pre NSPS); PC wet-bottom tangentially fired (NSPS); cyclone furnaces; spreader stokers; and overfeed stokers**.**

[c] Expressed as SO_2, SO_3 and gaseous sulfates. Similar to bituminous coal emissions, we assume over 95% of coal is emitted as SO_2. Value reported is average from all firing configurations reported, including PC dry-bottom wall-fired firing configurations (pre-NSPS and NSPS); PC dry bottom cell burner fired configurations; PC dry bottom tangentially fired (both pre-NSPS and NSPS); PC wet-bottom wall fired; cyclone furnaces; spreader stokers; and overfeed stokers.

[d] Because diesel is a distillate fuel, it is assumed that equivalent EFs. This EF applies only if input MW<30, which seems to be the case for the power plants burning diesel in the Energy Commission database. Based on sulfur content of diesel of 0.4% by weight (S_{diesel} = 0.4)

[e] Sulfur weight content of distillate oil is 0.2% ($S_{distillate}$ = 0.2).

[f] Uncontrolled turbines (including simple cycle, regenerative cycle, cogeneration cycles and combined cycle plants) operating at greater than or equal to 80% load. EFs in the AP 42 are given on a lb/MMBtu basis and are multiplied by the heating value of distillate fuel (**Table 3**), assuming a sulfur content of 0.2% by weight ($S_{distillate}$ = 0.2).

[g] Based on 100% conversion of fuel sulfur to SO_2 and assuming sulfur content of 2000 grains/10^6 scf.

[h] Based on plants operating at or above 80% load. Because the weight content of sulfur in natural gas is not available, AP 42 recommends 3.4 E-03 lb/MMBtu multiplied by the heating value of natural gas, 1035 Btu/scf.

[i] Based on plants operating at or above 80% load.

[j] Based on the average of the EFs for uncontrolled 2 stroke lean burn, 4-stroke lean and 4-stroke rich burn reciprocating engines (SCC = 2-02-002-52, 2-02-002-54, and 2-02-002-53, respectively) in AP42 (Section 3.2). EFs reported on lb/MMBtu basis and converted to lb/10^6scf using heating value of natural gas (1020 Btu/scf).

A-2b) Emission factors for NOx emissions

Primary Fuel	Technology	Emission Factors		
		Value	**Units**	**Rating**
Coal	Bottoming cycle, topping cycle, steam turbine, fluidized boiler, or not reported			
Bituminous		16.2[a]	lb/ton	A-E
Subbituminous		11.9[b]	lb/ton	A-E
Oil				
Distillate	Combustion or gas turbine	78.4[e]	lb/1000 gal	B & C
	Steam turbine	20[d]	lb/1000 gal	A
Diesel		20[c,d]	lb/1000 gal	A
Natural Gas	Combustion or gas turbine	189.4[h]	lb/10^6 scf	A,D
	Steam turbine			
	MW > 30	177.5[f]	lb/10^6 scf	A,D
	MW < 30	60.7[g]	lb/10^6 scf	B,C,D
	Reciprocating engine	$2.5x10^3$ [j]	lb/10^6 scf	A,B,C
WTE				
Digester gas	Gas turbine, combined cycle, or internal combustion	96[i]	lb/10^6 scf	D
Landfill gas	Brownfield, greenfield, active flare/LFGTE, gas turbine, steam turbine, methane gas, internal combustion, or reciprocating engines.	56[i]	lb/10^6 scf	A

[a] Average of all boiler types reported with the exception of overfeed and underfed stokers and hand-fed units. Boiler types included are: PC dry-bottom wall-fired firing configurations (pre-NSPS and NSPS); PC dry bottom cell burner fired configurations; PC dry bottom tangentially fired (both pre-NSPS and NSPS); PC wet-bottom wall fired; cyclone furnaces; spreader stokers; overfeed stokers; and circulating bed and bubbling bed FBC.

[b] Average of all boiler types reported with the exception of overfeed and underfed stokers and hand-fed units. Boiler types included are: PC dry-bottom wall-fired firing configurations (pre-NSPS and NSPS); PC dry bottom cell burner fired configurations; PC dry bottom tangentially fired (both pre-NSPS and NSPS); PC wet-bottom wall fired; cyclone furnaces; spreader stokers; and circulating bed and bubbling bed FBC.

[c] Because diesel is a distillate oil, the same EF for distillate oil fired steam turbine was used. This is based on NO_2.

[d] EF is expressed as NO_2, even though "over 95% of emitted NOx is in the form of nitrogen oxide (NO)" Section 1.3, p3 of AP 42.

[e] Average of uncontrolled and water-steam injection (including simple cycle, regenerative cycle, cogeneration cycles and combined cycle plants) operating at greater than or equal to 80% load. EFs in the AP 42 are given on a lb/MMBtu basis and are multiplied by the heating value of distillate fuel (**Table 3**).

[f] Expressed as NO_2. EFs are the average of uncontrolled (both pre-NSPS and post-NSPS) and controlled (low-NOx burner and flue gas recirculation units) large wall-fired steam boilers with greater than 30MW heat input.

[g] Expressed as NO_2. EFs are the average of uncontrolled and controlled (low NOX burner and flue gas recirculation) small boilers burning less than 30 MW heat input.

[h] Based on plants operating at or above 80% load. The average of three natural gas fired turbines (uncontrolled, water steam injection and lean-premix). EFs are reported on a lb/MMBtu basis and converted to lb/10^6 scf based on heating value of natural gas.

[i] Based on plants operating at or above 80% load.

[j] Based on the average of the EFs of all of the 90-105% load and <90% load EFs for NOx (none reported for unreported load conditions) from reciprocating engines including, 2 stroke lean burn, 4-stroke lean and 4-stroke rich burn reciprocating engines (SCC = 2-02-002-52, 2-02-002-54, and 2-02-002-53, respectively in AP 42 (Section 3.2). EFs are reported on lb/MMBtu basis and converted to lb/10^6scf using heating value of natural gas (1020 Btu/scf).

A-2c) Emission factors for PM2.5 emissions

Primary Fuel	Technology	Emission Factors		
		Value	Units	Rating
Coal	Bottoming cycle, topping cycle, steam turbine, fluidized boiler, or not reported			
Bituminous		0.91[a]	lb/ton	C,D,E
Subbituminous		0.10[b]	lb/ton	C,D,E
Oil				
Diesel		0.54 [c,d]	lb/1000 gal	D & E
Distillate	Steam turbine	0.54 [d]	lb/1000 gal	D & E
	Combustion and gas turbine	1.01[e]	lb/1000 gal	C
Natural Gas	Combustion or gas turbine	4.9[f]	lb/10^6 scf	C
	Steam turbine	negligible		
	Reciprocating engines	12.8[g]	lb/10^6 scf	C,D,E
WTE				
Digester gas	Gas turbine, combined cycle, or internal combustion	n/a		
Landfill gas	Brownfield, greenfield, active flare/LFGTE, gas turbine, steam turbine, methane gas, internal combustion, or reciprocating engines.	n/a		

[a] Average of EFs from technologies reported burning bituminous coal, including PC, dry-bottom, wall-fired firing configurations (for uncontrolled plants as well as plants with either multiple cyclone, scrubber, ESP, or baghouse); PC, dry bottom, tangentially fired plants which are either uncontrolled plants as well as plants with either multiple cyclone, scrubber, ESP, or baghouses); PC, wet-bottom, wall-fired and tangentially fired plants that are either uncontrolled, with multiple cyclones or with ESP technology; spreader stokers which are either uncontrolled or have multiple cyclone, ESP or baghouse technology; and overfeed stokers which are either uncontrolled or have multiple cyclone technology.

[b] Average of EFs from technologies reported burning subbituminous coal, including PC, dry-bottom, wall-fired firing configurations (for uncontrolled plants as well as plants with either multiple cyclone, scrubber, ESP, or baghouse) and PC, dry bottom, tangentially fired plants which are either uncontrolled plants as well as plants with either multiple cyclone, scrubber, ESP, or baghouses.

[c] Because diesel is a distillate oil, the same EF as for PM2.5 from distillate oil fired steam turbine was used. This is based on NO_2.

[d] The average of commercial and industrial boilers.

[e] Uncontrolled turbines including simple cycle, regenerative cycle, cogeneration cycles and combined cycle plants, operating at or above 80% load.

[f] Based on condensable PM emissions from water-steam injection gas-fired turbines. Assumes plants operate at or above 80% load.

[g] EFs are the average of the reported filterable (< 1mm aerodynamic diameter) and condensable PM2.5 from three types of reciprocating engines, including 2 stroke lean burn, 4-stroke lean and 4-stroke rich burn reciprocating engines (SCC = 2-02-002-52, 2-02-002-54, and 2-02-002-53, respectively) from the AP 42. However, for the condensable PM2.5, there is no EF data available from 2-stroke lean and 4-stroke rich engines, therefore the EFs reflect emissions from 4SLB engines. Condensable PM2.5 EFs from 4-stroke lean refers to inorganic and organic PM condensable emissions. EFs are reported on lb/MMBtu basis and converted to lb/10^6scf using heating value of natural gas (1020 Btu/scf).

A-2d) Emission factors for BaP emissions

Primary Fuel	Technology	Emission Factors		
		Value	Units	Rating
Coal	Bottoming cycle, topping cycle, steam turbine, fluidized boiler, or not reported			
Bituminous		3.8E-08[a]	lb/ton	D
Subbituminous		3.8E-08[a]	lb/ton	D
Oil				
Diesel		0.006 [b]	lb/1000 gal	C
Distillate	Steam turbine	0.006 [b]	lb/1000 gal	C
	Combustion or gas turbine	0.006 [c]	lb/1000 gal	C
Natural Gas	Combustion or gas turbine	2.28E-03[e]	lb/10^6 scf	C
	Steam turbine	1.2E-06[d]	lb/10^6 scf	E
	Reciprocating engine	5.9E-06[f]	lb/10^6 scf	D
WTE				
Digester gas	Gas turbine, combined cycle, or internal combustion	n/a		
Landfill gas	Brownfield, greenfield, active flare/LFGTE, gas turbine, steam turbine, methane gas, internal combustion, or reciprocating engines.	n/a		

[a] EF based on plants that are either PC, dry-bottom, wall-fired and cell-burner firing configurations and Cyclone furnaces. Bituminous and subbituminous distinction not reported.

[b] EFs are not reported in the AP 42 for diesel nor distillate oil fired steam turbine power plants. Assume that the gas-fired stationary turbines for which there are EFs are applicable. Note however, that in general, EFs from steam turbines tend to be less than half of the EFs from distillate oil gas turbine plants.

[c] EF reported for "PAH" and we assume that this applies to BaP (Table 3.1.4 in AP 42). Further, EFs estimated from uncontrolled turbines including simple cycle, regenerative cycle, cogeneration cycles and combined cycle plants, operating at or above 80% load.

[d] The method detection limit (MDL). The EF is either at or below MDL.

[e] EFs are given for "PAH" in general (Table 3.1.3 of the AP 42) and it is assumed that this applies to BaP. EFs are based on uncontrolled gas-fired turbines operating at or above 80% load.

[f] Only EFs for uncontrolled 2-stroke lean burn engines (SCC 2-02-002-52) are reported in the AP42, Section 3.2. EFs are reported on lb/MMBtu basis and converted to lb/10^6scf using heating value of natural gas (1020 Btu/scf).

A-2e) Emission factors for benzene emissions

Primary Fuel	Technology	Emission Factors		
		Value	Units	Rating
Coal	Bottoming cycle, topping cycle, steam turbine, fluidized boiler, or not reported			
Bituminous		1.3E-03[a]	lb/ton	A
Subbituminous		1.3E-03[a]	lb/ton	A
Oil				
Diesel		2.14E-04[b]	lb/1000 gal	C
Distillate	Steam turbine	2.14E-04[b]	lb/1000 gal	C
	Combustion and gas turbine	7.7E-03[c]	lb/1000 gal	C
Natural gas	Combustion or gas turbine	1.24E-02[d]	lb/10^6 scf	A
	Steam turbine	2.10E-03	lb/10^6 scf	B
	Reciprocating engine	1.4[f]	lb/10^6 scf	A & B
WTE				
Digester gas	Gas turbine, combined cycle, or internal combustion	n/a		
Landfill gas	Brownfield, greenfield, active flare/LFGTE, gas turbine, steam turbine, methane gas, internal combustion, or reciprocating engines.	8.4E-03[e]	lb/10^6 scf	B

[a] EF based on plants that are either PC, dry-bottom, wall-fired and cell-burner firing configurations and cyclone furnaces. Bituminous and subbituminous distinction not reported.

[b] Reported for residual oil (Table 1.3-9 in AP 42) and we assume this applies for diesel and distillate oil.

[c] Uncontrolled turbines including simple cycle, regenerative cycle, cogeneration cycles and combined cycle plants, operating at or above 80% load.

[d] EFs are given for uncontrolled natural gas gas-fired turbines and are converted from lb/MMBtu. The EF assumes that a plant operates at or above 80% load.

[e] For plants operating at or above 80% load.

[f] Average EF reported for three types of reciprocating engines, including 2 stroke lean burn, 4-stroke lean and 4-stroke rich burn reciprocating engines (SCC = 2-02-002-52, 2-02-002-54, and 2-02-002-53, respectively) from the AP 42. EFs are reported on lb/MMBtu basis and converted to lb/10^6scf using heating value of natural gas (1020 Btu/scf).

A-2f) Emission factors for naphthalene emissions

Primary Fuel	Technology	Emission Factors		
		Value	Units	Rating
Coal	Bottoming cycle, topping cycle, steam turbine, fluidized boiler, or not reported			
Bituminous		1.3E-05[a]	lb/ton	C
Subbituminous		1.3E-05[a]	lb/ton	C
Oil				
Diesel		1.13E-03[b]	lb/1000 gal	C
Distillate	Steam turbine	1.13E-03[b]	lb/1000 gal	C
	Combustion or gas turbine	4.9E-03[c]	lb/1000 gal	C
Natural gas	Combustion or gas turbine	1.35E-03[d]	lb/10^6 scf	C
	Steam turbine	6.10E-04	lb/10^6 scf	E
	Reciprocating engine	9.2E-02[e]	lb/10^6 scf	C,E
WTE				
Digester gas	Gas turbine, combined cycle, or internal combustion	n/a		
Landfill gas	Brownfield, greenfield, active flare/LFGTE, gas turbine, steam turbine, methane gas, internal combustion, or reciprocating engines.	n/a		

[a] EF based on plants that are either PC, dry-bottom, wall-fired and cell-burner firing configurations and cyclone furnaces. Bituminous and subbituminous distinction not reported.

[b] Reported for residual oil (Table 1.3-9 in AP 42) and we assume this applies for diesel and distillate oil.

[c] Uncontrolled turbines including simple cycle, regenerative cycle, cogeneration cycles and combined cycle plants, operating at or above 80% load.

[d] EFs are given for uncontrolled natural gas gas-fired turbines and are converted from lb/MMBtu. The EF assumes that a plant operates at or above 80% load.

[e] Average EF reported for three types of reciprocating engines, including 2 stroke lean burn, 4-stroke lean and 4-stroke rich burn reciprocating engines (SCC = 2-02-002-52, 2-02-002-54, and 2-02-002-53, respectively) from the AP 42. EFs are reported on lb/MMBtu basis and converted to lb/10^6scf using heating value of natural gas (1020 Btu/scf).

Table A-3: Heating value (HV) of the fuel types

Fuel	HV	Units	Reference
Coal			
Bituminous [a]	13,000	Btu/lb	App A, AP 42
Subbituminous	11,900	Btu/lb	EIA, 2002
Lignite	7200	Btu/lb	App A, AP 42
Oil			
Diesel	137,000	Btu/gal	App A, AP 42
Distillate	140,000	Btu/gal	App A, AP 42
Natural gas	1035	Btu/scf	AP 42 [b]
WTE			
Digester gas	600	Btu/scf at 60 °F	AP 42, Section 3.1
Landfill gas	400	Btu/scf at 60 °F	AP 42, Section 3.1
Crude Oil	19,000 [c]	Btu/lb	http://www.eppo.go.th/ref/UNIT-OIL.html
Petroleum coke	13,300 [d]	Btu/lb	App A, AP 42

[a] Assumes bituminous coal burned in California

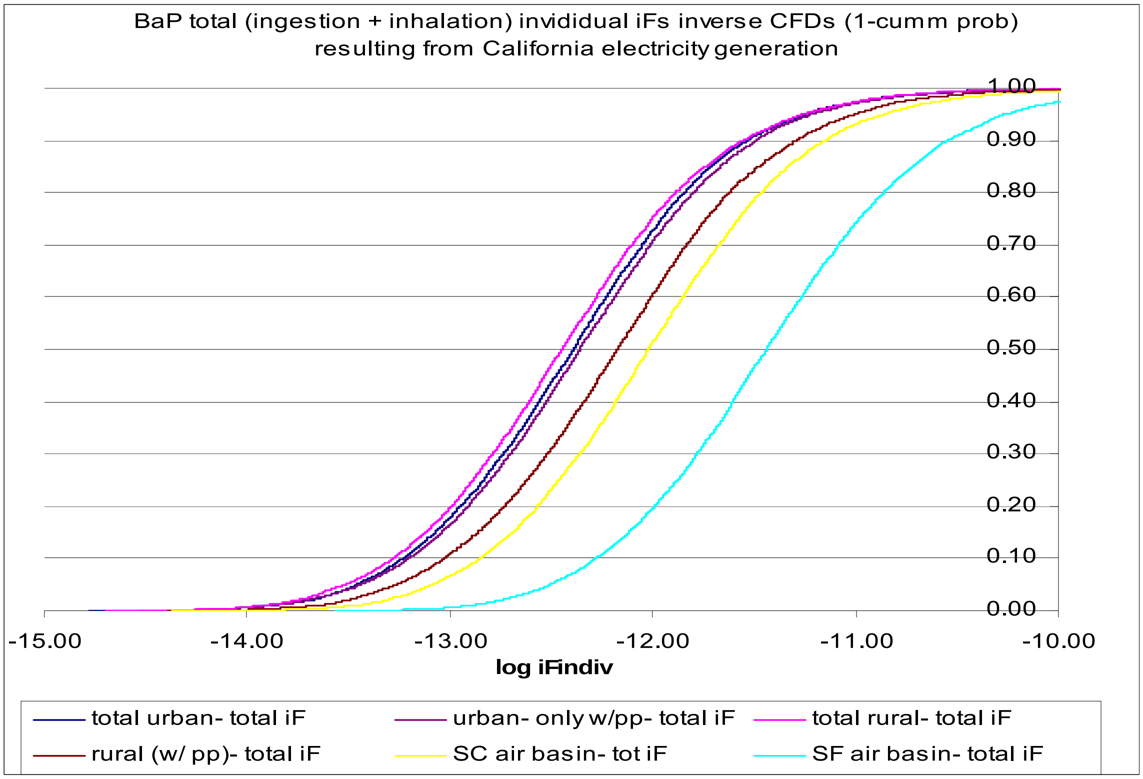
[b] Average of two values reported in Appendix A (p 5) and Chapter 1.4 of AP 42

[c] Approximately 15% greater heating value than coal

[d] Assumes 'coke, byproduct' heating value.

Appendix B

Intermediate Results for the Individual Intake Fraction and Effect Factors Used to Calculate Human Damage Factors (HDFs)



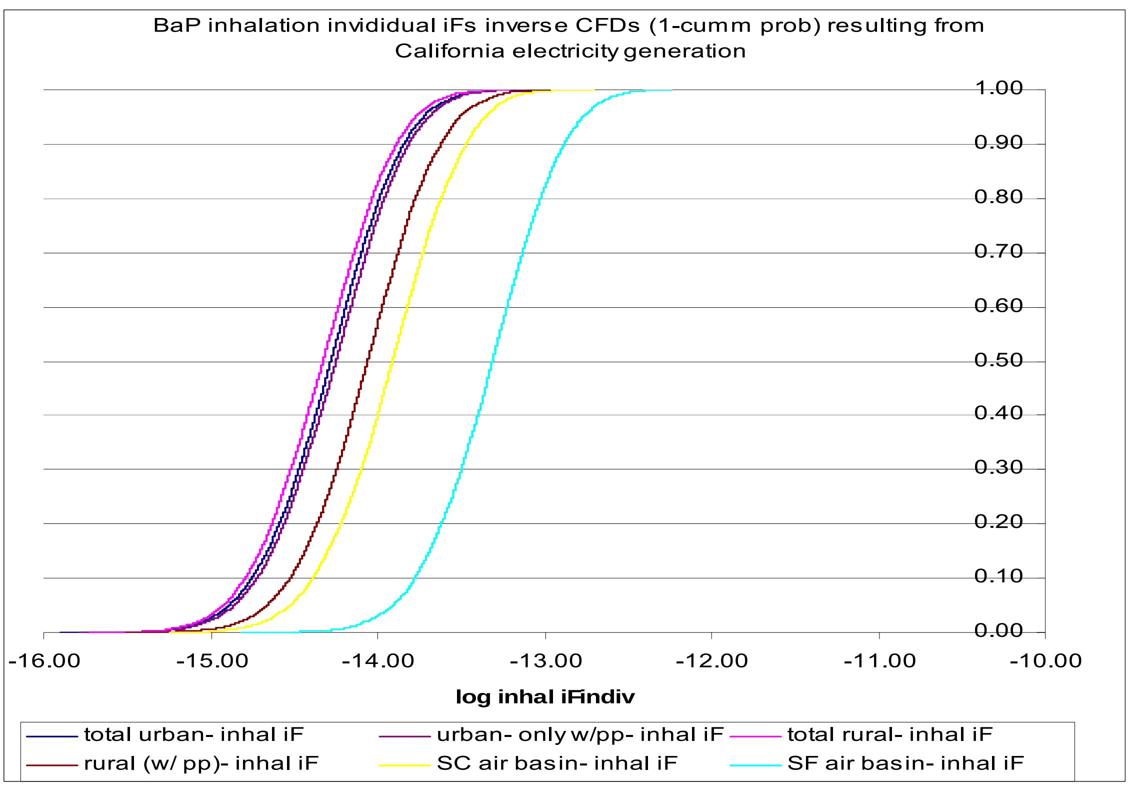


Figure B-1. Distribution of individual intake fraction (*iFi)* for BaP based on total (ingestion and inhalation) intake (upper chart) and intake and only inhalation intake (lower chart)

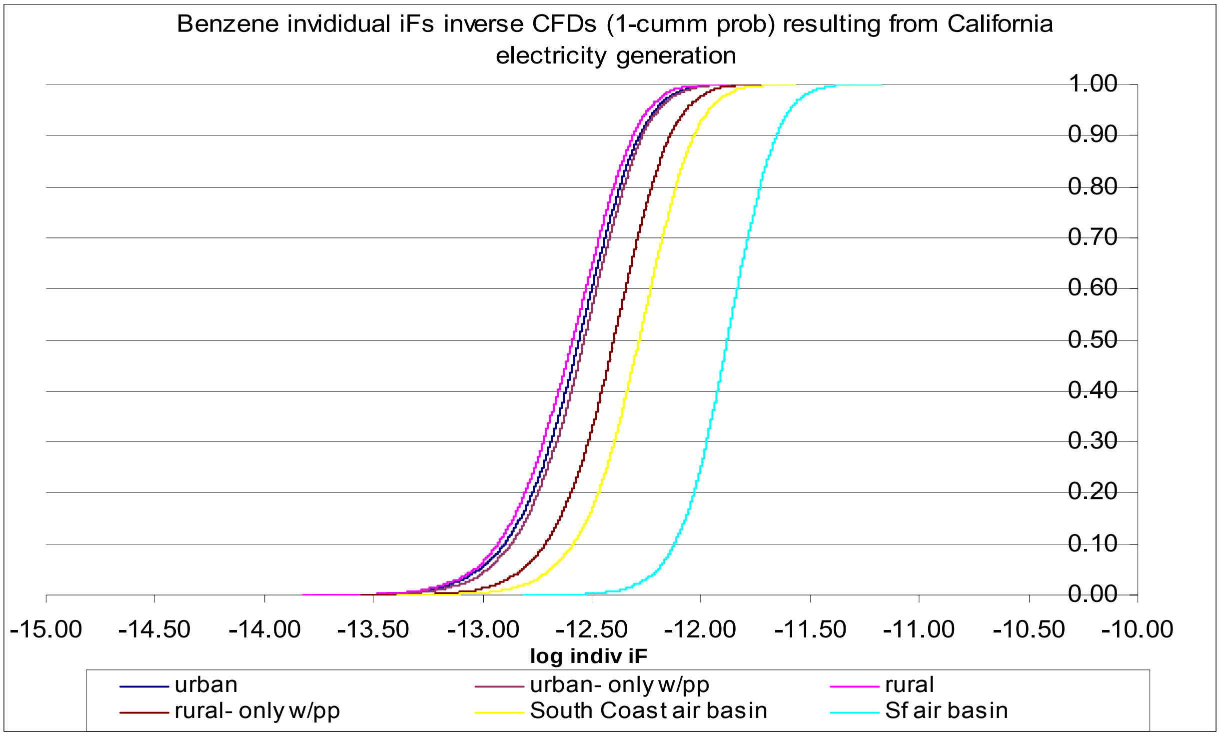


Figure B-2. Benzene *iFi* distributions

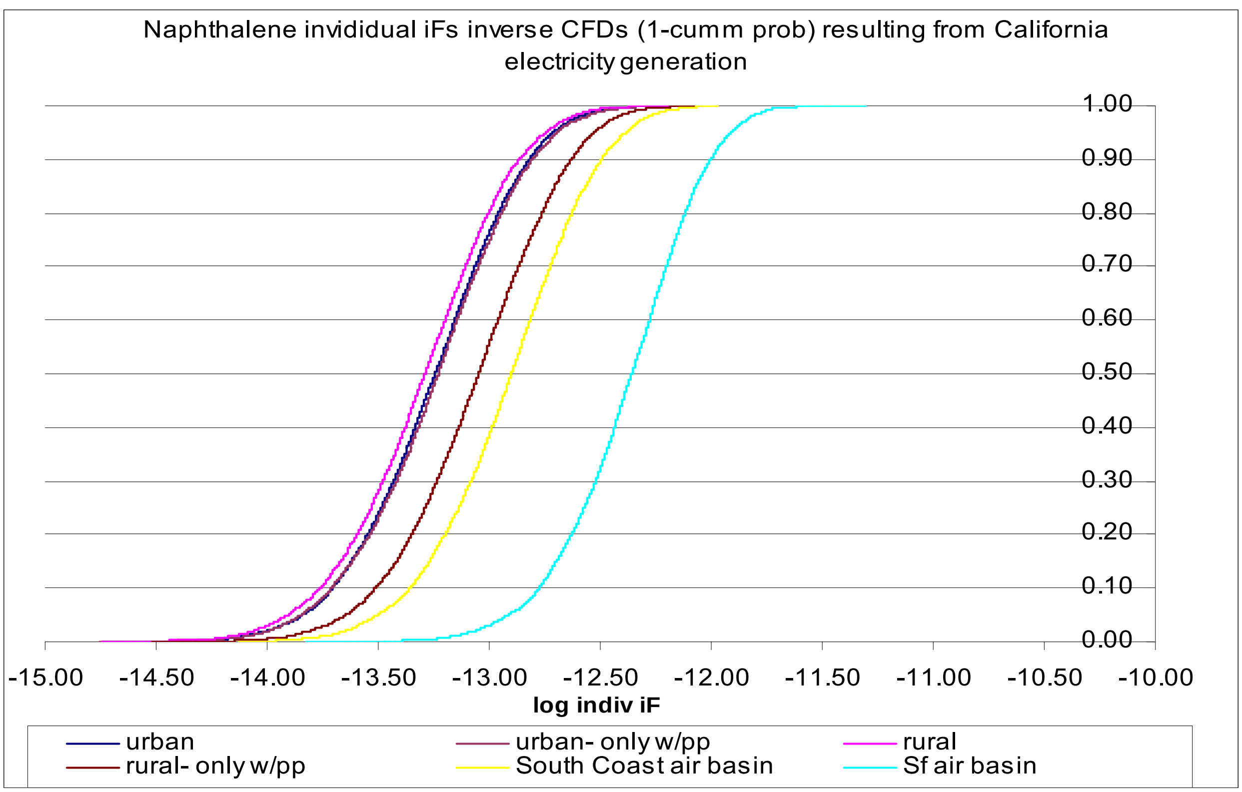


Figure B-3. Naphthalene *iFi* distributions

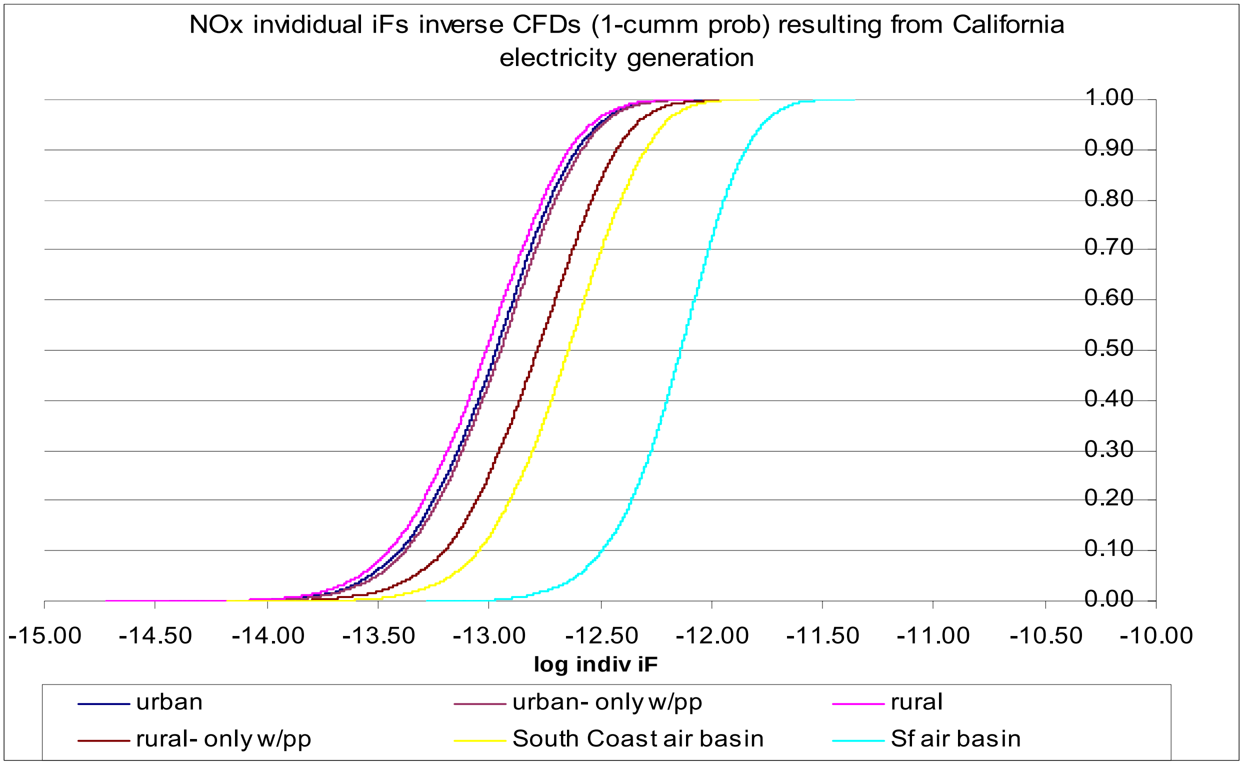


Figure B-4. NOx *iFi* distributions

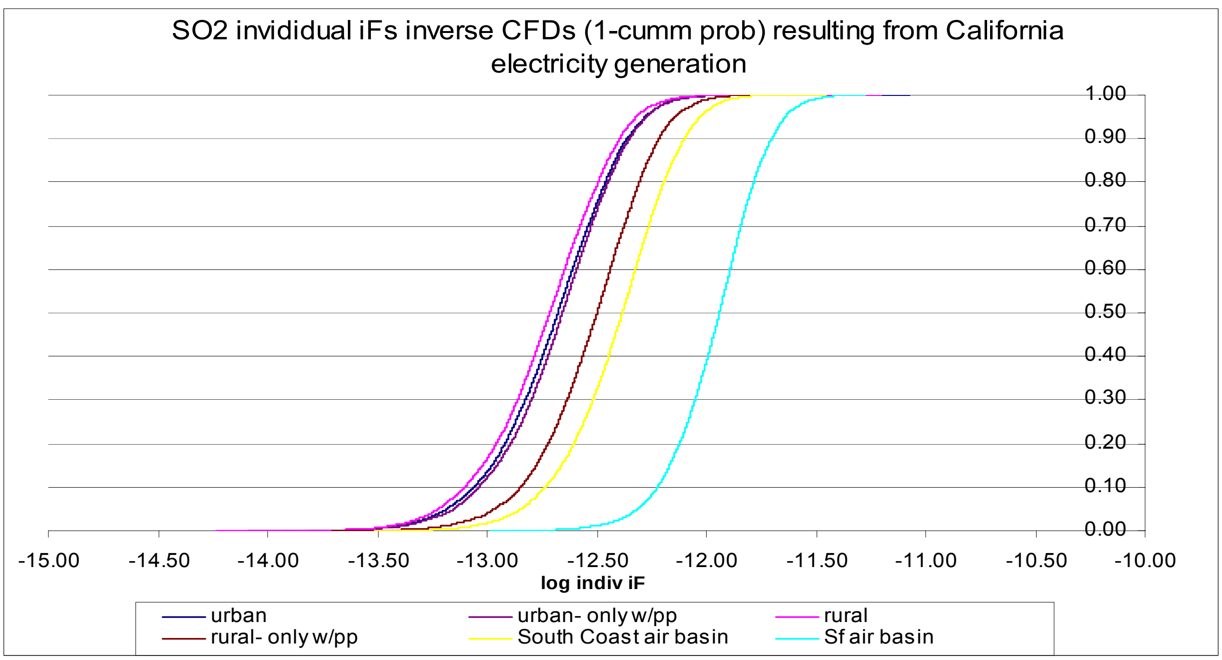


Figure B-5. SO_2 *iFi* distributions

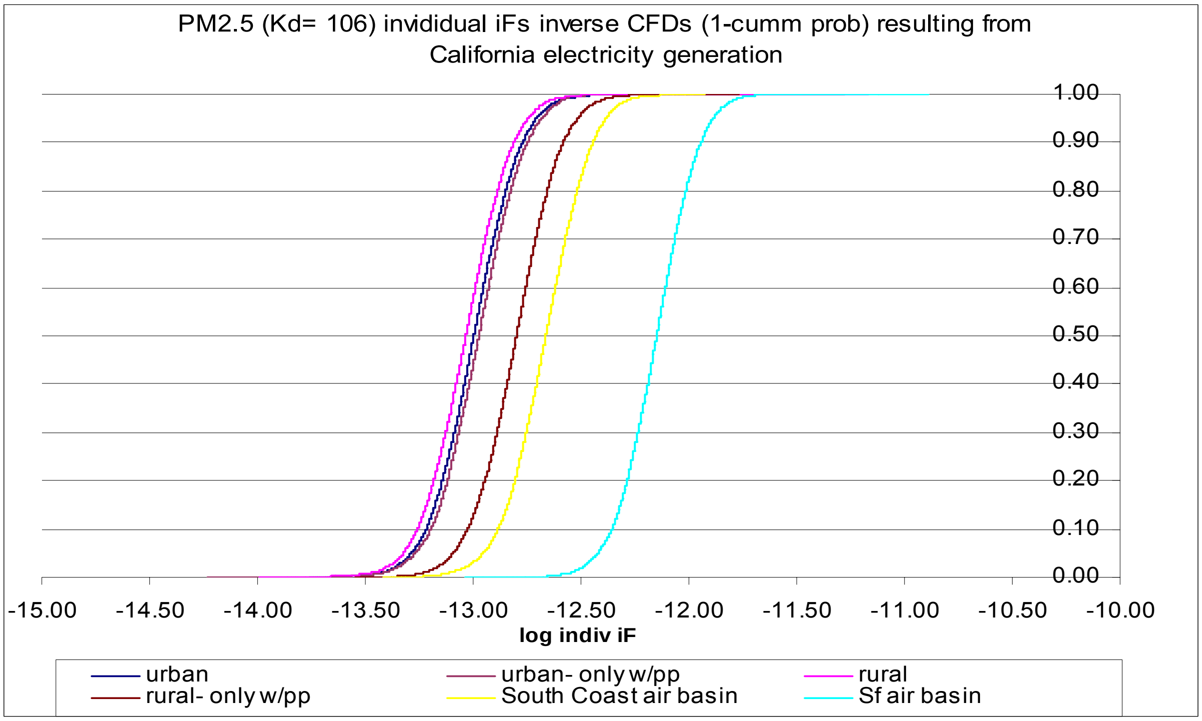


Figure B-6a. PM2.5 *iFi* distributions, assuming Kd= 10^6

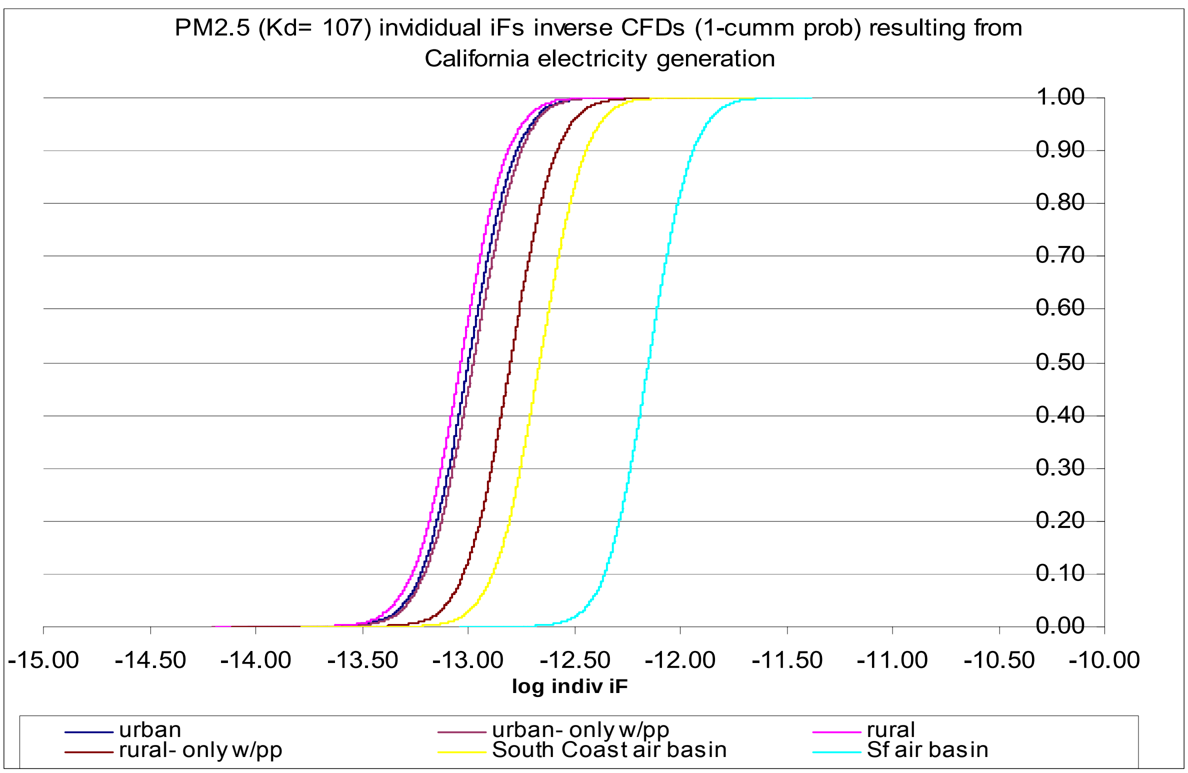


Figure B-6b: PM2.5 *iFi* distributions, assuming Kd= 10^7

Table B-1 (a&b): The carcinogenic effect factor, EFx, for each chemical x, derived based on the methodology of a) Crettaz et al. (2002) and b) Huijbregts et al. (2005).

Table B-1a. EFx estimates based on Crettaz et al. (2002) methods using default DALYp of 6.7 y. The EFx based on specific cancer endpoint is given in parentheses (i.e., DALYp= 13.0 for lung cancer associated with BaP exposure, and 14.6 for leukemia associated with benzene exposure)

	β_{ED10h} risk/(mg/kg BW/d)	**β_{ED10h} derivation comment**	**EFx (DALY/mg intake)**
benzene	3.9×10^{-3}	Lower bound of range on q1* (inhalation→oral)	1.4×10^{-8} (3.1×10^{-8})
	1.4×10^{-2}	Upper bound of range on q1* (inhalation → oral)	5.1×10^{-8} (1.1×10^{-7})
	2.4×10^{-2}	ED10h from TD50a (rat); theoretical estimation	8.9×10^{-8} (1.9×10^{-7})
	1.5×10^{-2}	ED10h from TD50a (rat) empirical regression	5.5×10^{-8} (1.2×10^{-7})
B(a)P	2.3	Lower bound of range on q1* (oral)	8.4×10^{-6} (1.6×10^{-5})
	5.9	Upper bound of range on q1* (oral)	2.2×10^{-5} (4.3×10^{-5})
	4.2	ED10h from TD50a (rat); theoretical estimation	1.6×10^{-5} (3.0×10^{-5})
	2.6	ED10h from TD50a (Rat); empirical regression	9.8×10^{-6} (1.9×10^{-5})
Naphthalene	2.5×10^{-2}	ED10h from TD50a (mouse); theoretical estimation	9.2×10^{-8}
	1.5×10^{-2}	ED10h from TD50a (mouse); empirical regression	5.7×10^{-8}
PM2.5	8.8	based on 1 ug/m3 increase in annual PM2.5 mean concentrations leading to a 0.4% increase in premature deaths (Pope et al., 2002)	3.1×10^{-5}

Table B-1b. EFx estimates based on the methods of Huijbregts et al. (2005).

	ED50x,r [kg]	**Effect Factor derivation comment**	**EFx (DALY/mg intake)**
benzene	79.2	using specific DALYe and p(d|ΔTU) for trachea, bronchus, and lung cancer 0.026, 16.5	5.4×10^{-9}
		using default DALYe and p(d|ΔTU) for cancer	4.4×10^{-9}
	103.9	using lower bound of q* (inhal) reported in IRIS	3.3×10^{-9}
	29.3	using upper bound of q* (inhal) reported in IRIS	1.2×10^{-8}
B(a)P	0.4	using specific DALYe and p(d|ΔTU) for stomach cancer (0.035, and 13.6)	1.1×10^{-6}
		using default DALYe and p(d|ΔTU) for cancer	7.7×10^{-7}
	0.2	using lower bound of q* (oral) reported in IRIS	1.9×10^{-6}
	0.1	using upper bound of q* (oral) reported in IRIS	5.0×10^{-6}
Naphthalene	44.9	using specific DALYe and p(d|ΔTU) for stomach cancer (0.035, 13.6)	1.1×10^{-8}
		using default DALYe and p(d|ΔTU) for cancer	7.7×10^{-9}
PM2.5	4.6×10^{-2}	using default DALYe and p(d|ΔTU) for cancer	6.0×10^{-6}

Appendix C

List of (a) Urban and (b) Rural Power Plants and Their Associated Fuel Type and Technology and Online MWe Sorted by County of Location

Information in the following tables comes from the California Energy Commission's 2004 Database of California Power Plants, www.energy.ca.gov/database/index.html#powerplants.

a) Urban power plants

PLANTNAME	PRIMARY FUEL	TECHNOLOGY	COGEN	COUNTY	ONLINE MW
Oakland	Distillate Oil	Gas Turbine	Not Cogen	Alameda	165
Alameda	Natural Gas	Combustion Turbine	Not Cogen	Alameda	51.65
Stanford Energy Group	Natural Gas		Cogen	Alameda	0.115
Borden Chemical	Natural Gas		Cogen	Alameda	0.2
Summit Medical Cogen	Natural Gas		Cogen	Alameda	2.86
Continental Can - White Cap	Natural Gas		Not Cogen	Alameda	0.6
PE – Berkeley Inc.	Natural Gas, Distill	Combined Cycle	Cogen	Alameda	28.5
Altamont Gas Recovery	Landfill Gas	Active -Flare/Lfgte	Not Cogen	Alameda	7
Gas Recovery Systems - Fremont	Msw	Landfill Gas	Not Cogen	Alameda	3.75
Oroville Cogen	Natural Gas	Gas Turbine	Cogen	Butte	8.05
Pacific Oroville Power Inc.	Ag. & Woodwaste		Not Cogen	Butte	18.75
Nichols Road Power Plant	Pet Coke, Crude Oil	Fluidized Boiler	Not Cogen	Contra Costa	19
Wilbur West Power Plant	Pet Coke, Crude Oil	Fluidized Boiler	Not Cogen	Contra Costa	19
Loveridge Road Power Plant	Pet Coke, Crude Oil	Fluidized Boiler	Not Cogen	Contra Costa	19
East Third Street Power Plant	Pet Coke, Crude Oil	Fluidized Boiler	Not Cogen	Contra Costa	19
Wilbur East Power Plant	Pet Coke, Crude Oil	Steam Turbine	Not Cogen	Contra Costa	19

Los Medanos Energy Center	Natural Gas	Cogeneration, Steam To Uss-Posco	Not Cogen	Contra Costa	555
Delta Energy Center	Natural Gas	Combined Cycle Cogeneration Steam To Dow	Cogen	Contra Costa	861
Mobile Gt	Natural Gas	Gas Combustion Turbine	Not Cogen	Contra Costa	45
Chevron - Concord	Natural Gas	Gas Turbine	Cogen	Contra Costa	3
Foster-Wheeler Martinez Cogen L.P.	Natural Gas	Gas Turbine	Cogen	Contra Costa	113.5
Crockett Cogen	Natural Gas	Gas Turbine	Cogen	Contra Costa	247.4
Riverview Energy Center	Natural Gas	Gas Turbine		Contra Costa	47.3
Richmond Cogen	Natural Gas	Gas Turbine Turbine	Cogen	Contra Costa	125.28
Martinez Refining Co.	Natural Gas	Gas Turbine, Steam Turbine	Cogen	Contra Costa	99
Rhone-Poulenc - Stauffer Chemical	Natural Gas	Gas Turbine/Heat Recovery Steam Generatr	Cogen	Contra Costa	4
Brookside Hospital	Natural Gas	Internal Combustion	Cogen	Contra Costa	0.949
C & H Sugar	Natural Gas	Steam Turbine, Waste Heat	Cogen	Contra Costa	9.5
Contra Costa	Natural Gas	Steam Turbine	Not Cogen	Contra Costa	672
Pittsburg	Natural Gas	Steam Turbine	Not Cogen	Contra Costa	1332
City Of Concord	Natural Gas		Cogen	Contra Costa	0.105
Tosco Sfar Carbon	Natural Gas		Cogen	Contra Costa	27.38
San Francisco Refinery	Natural Gas		Cogen	Contra Costa	49.9
Calpine Pittsburg	Natural Gas, Hydro	Gas Turbine	Cogen	Contra Costa	74

Nove Power Plant	Landfill Gas	Internal Combustion	Not Cogen	Contra Costa	3
Fresno Cogen	Natural Gas	Combined Cycle	Cogen	Fresno	25
Saint Agnes Hospital	Natural Gas	Gas Turbine	Cogen	Fresno	2.325
Al Resources	Natural Gas	Gas Turbine/Heat Recovery Steam Generatr	Cogen	Fresno	8.5
Coalinga	Natural Gas	Gas Turbine/Heat Recovery Steam Generatr	Cogen	Fresno	20.7
Fresno Cogen Partners Lp Pkr	Natural Gas		Cogen	Fresno	21.3
Sanger Power & Feed	Natural Gas		Cogen	Fresno	39.8
Roy Sharp Jr.	Natural Gas		Not Cogen	Fresno	0.1
Wellhead Power Gates, Llc	Natural Gas		Not Cogen	Fresno	46.5
Wellhead Power Panoche, Llc	Natural Gas		Not Cogen	Fresno	49.9
Calpeak Power Panoche, Llc	Natural Gas			Fresno	49.615
Pe - Kes Kingsburg Llc	Natural Gas, Distill		Cogen	Fresno	34.5
Coalinga Cogen Co.	Natural Gas/Eor	Gas Turbine	Cogen	Fresno	38
Rio Bravo Fresno	Woodwaste	Steam Turbine	Not Cogen	Fresno	24.3
Mendota Biomass Power Ltd	Woodwaste	Steam Turbine, Cfb	Cogen	Fresno	25
Hanford	Petroleum Coke, Crud	Fluidized Boiler	Cogen	Kings	24
Kings County State Prison	Natural Gas		Cogen	Kings	5.2
Gwf Henrietta	Natural Gas		Not Cogen	Kings	96

Gwf Hanford Peaker	Natural Gas	Brown Field	Not Cogen	Kings	95
Dinuba Energy Inc.	Ag. & Woodwaste		Cogen	Kings	12
Arco Wilmington Calciner	Petroleum Coke	Coal Fired Bottoming Cycle	Cogen	Los Angeles	35.8
Pebbly Beach	Diesel	Internal Combustion	Not Cogen	Los Angeles	9.4
Diesels	Diesel		Not Cogen	Los Angeles	26
Alamitos Generating Station	Distillate Oil	Steam Turbine, Gas Turbine	Not Cogen	Los Angeles	2087
Cotija Cheese	Natural Gas	Xeration	Cogen	Los Angeles	0.12
Linde Wilmington	Natural Gas	Combined Cycle	Cogen	Los Angeles	28
Harbor	Natural Gas	Combined Cycle, Gas Turbine	Cogen	Los Angeles	472
Lundy - Thagard Oil	Natural Gas	Combined Cycle/Topping Cycle	Cogen	Los Angeles	1.4
N.P. Cogen Inc.	Natural Gas	Combined Cycle/Topping Cycle	Cogen	Los Angeles	24.7
San Gabriel Cogen	Natural Gas	Combined Cycle/Topping Cycle	Cogen	Los Angeles	36
Glenarm	Natural Gas	Combustion Turbine	Not Cogen	Los Angeles	60.8
Long Beach	Natural Gas	Combustion Turbine, Steam Turbine	Not Cogen	Los Angeles	577
St. John's Hospital And Health Center	Natural Gas	Combustion Turbine/Topping Cycle	Cogen	Los Angeles	1.08
Pomona Power Facility	Natural Gas	Combustion Turbine/Topping Cycle	Cogen	Los Angeles	3.3
Jefferson Smurfit Corp.	Natural Gas	Combustion Turbine/Topping Cycle	Cogen	Los Angeles	40

Coldgen - Sunlaw Cogen #1	Natural Gas	Combustion Turbine/Topping Cycle	Cogen	Los Angeles	56
Coldgen - Sunlaw Cogen #2	Natural Gas	Combustion Turbine/Topping Cycle	Cogen	Los Angeles	56
Santa Monica Bay Hotel	Natural Gas	Ct/Industrial Topping Cycle	Cogen	Los Angeles	0.95
Vanguard - Electronic Plating	Natural Gas	Gas Fueled Reciprocating Engine	Cogen	Los Angeles	0.1
Whittier Uhsd - La Serna Hs	Natural Gas	Gas Fueled Reciprocating Engine	Cogen	Los Angeles	0.1
The Forum #1	Natural Gas	Gas Fueled Reciprocating Engine	Cogen	Los Angeles	0.115
The Episcopal Home	Natural Gas	Gas Fueled Reciprocating Engine	Cogen	Los Angeles	0.2
Southern California Gas	Natural Gas	Gas Fueled Reciprocating Engine	Cogen	Los Angeles	0.55
Great Western Malting Co.	Natural Gas	Gas Fueled Reciprocating Engine	Cogen	Los Angeles	0.75
Biola University	Natural Gas	Gas Turbine	Cogen	Los Angeles	1.2
Smurfit Pomona Mill	Natural Gas	Gas Turbine	Cogen	Los Angeles	16.3
Pitchess Cogen	Natural Gas	Gas Turbine	Cogen	Los Angeles	28.3
Norwalk Energy	Natural Gas	Gas Turbine	Cogen	Los Angeles	30.75
UCLA Cogen	Natural Gas	Gas Turbine	Cogen	Los Angeles	43
Los Angeles Refinery	Natural Gas	Gas Turbine	Cogen	Los Angeles	68.5
Harbor Cogen	Natural Gas	Gas Turbine	Cogen	Los Angeles	81.7
Texaco Los Angeles Refinery	Natural Gas	Gas Turbine	Not Cogen	Los Angeles	60
Anderson Litograph Co.	Natural Gas	Gas Turbine Combined Cycle	Cogen	Los Angeles	5
Civic Center Cogen	Natural Gas	Gas Turbine, Steam Turbine	Cogen	Los Angeles	34.5

O'brien California Cogen	Natural Gas	Gas Turbine, Steam Turbine	Cogen	Los Angeles	34.5
Carson Cogen Co.	Natural Gas	Gas Turbine, Steam Turbine	Cogen	Los Angeles	49.5
Torrance Refinery	Natural Gas	Gas Turbine, Steam Turbine	Cogen	Los Angeles	222.7
Watson Cogen	Natural Gas	Gas Turbine, Steam Turbine	Cogen	Los Angeles	398
Aes Placerita	Natural Gas	Gas Turbine/Steam Turbine	Cogen	Los Angeles	150
Micro Utility - Safe Planting	Natural Gas	Gas-Fueled Reciprocating Engine	Cogen	Los Angeles	0.1
Micro Utility - Foss Planting	Natural Gas	Gas-Fueled Reciprocating Engine	Cogen	Los Angeles	0.1
Xic - Erne Sanitarium	Natural Gas	Gas-Fueled Reciprocating Engine	Cogen	Los Angeles	0.1
Micro Utility - Quaker	Natural Gas	Gas-Fueled Reciprocating Engine	Cogen	Los Angeles	0.1
Cal Poly University - Pomona	Natural Gas	Gas-Fueled Reciprocating Engine	Cogen	Los Angeles	0.115
La Canada Usd - La Canada School	Natural Gas	Gas-Fueled Reciprocating Engine	Cogen	Los Angeles	0.12
Mt. San Antonio Gardens	Natural Gas	Gas-Fueled Reciprocating Engine	Cogen	Los Angeles	0.12
City Of Long Beach - Belmont Plaza Pool	Natural Gas	Gas-Fueled Reciprocating Engine	Cogen	Los Angeles	0.12
Bixby Knolls Towers	Natural Gas	Gas-Fueled Reciprocating Engine	Cogen	Los Angeles	0.124
Cerritos College	Natural Gas	Gas-Fueled Reciprocating Engine	Cogen	Los Angeles	0.15
Csu Long Beach - Dorm	Natural Gas	Gas-Fueled Reciprocating Engine	Cogen	Los Angeles	0.15

Csu Long Beach - Pool	Natural Gas	Gas-Fueled Reciprocating Engine	Cogen	Los Angeles	0.2
Claremont Tennis Club	Natural Gas	Gas-Fueled Reciprocating Engine	Cogen	Los Angeles	0.2
Metal Surfaces	Natural Gas	Gas-Fueled Reciprocating Engine	Cogen	Los Angeles	0.35
Henry Mayo Newhall Memorial Hospital	Natural Gas	Gas-Fueled Reciprocating Engine	Cogen	Los Angeles	0.45
Presbyterian Intercommunity Hospital	Natural Gas	Gas-Fueled Reciprocating Engine	Cogen	Los Angeles	0.48
Petrominerals Corp.	Natural Gas	Gas-Fueled Reciprocating Engine	Cogen	Los Angeles	0.5
Pomona Valley Community Hospital	Natural Gas	Gas-Fueled Reciprocating Engine	Cogen	Los Angeles	0.8
Queen Mary	Natural Gas	Gas-Fueled Reciprocating Engine	Cogen	Los Angeles	1
Paper Pak Products	Natural Gas	Gas-Fueled Reciprocating Engine	Cogen	Los Angeles	1.4
Placerita Unit I	Natural Gas	I.C. Topping Cycle	Cogen	Los Angeles	21.76
Placerita Unit Ii	Natural Gas	I.C. Topping Cycle	Cogen	Los Angeles	21.76
Los Angeles Cold Storage	Natural Gas	Internal Combustion	Cogen	Los Angeles	1.35
Vernon	Natural Gas	Internal Combustion	Not Cogen	Los Angeles	30.6
Dex	Natural Gas	Natural Gas	Cogen	Los Angeles	0.5
Bentley Mills	Natural Gas	Photovoltaic Engine	Cogen	Los Angeles	0.8
Rhone-Poulenc - Dominguez Plant	Natural Gas	Process Steam Plant/Bottoming Cycle	Cogen	Los Angeles	4.9
Lake One	Natural Gas	Reclaimed Water	Not Cogen	Los Angeles	47

Grayson	Natural Gas	Steam & Combustion Turbine, Comb. Cycle	Not Cogen	Los Angeles	272.5
Arco Petroleum Products Co.	Natural Gas	Steam Turbine	Cogen	Los Angeles	13.5
Broadway	Natural Gas	Steam Turbine	Not Cogen	Los Angeles	162
El Segundo	Natural Gas	Steam Turbine	Not Cogen	Los Angeles	708
Magnolia	Natural Gas	Steam Turbine, Combined Cycle	Not Cogen	Los Angeles	81.7
California Institute Of Technology	Natural Gas	Steam Turbine, Gas Turbine	Cogen	Los Angeles	5.3
Olive	Natural Gas	Steam Turbine, Gas Turbine	Not Cogen	Los Angeles	152.5
Valley	Natural Gas	Steam Turbine, Natural Gas	Not Cogen	Los Angeles	517
Scattergood	Natural Gas	Steam Turbine, Natural Gas	Not Cogen	Los Angeles	803
Haynes	Natural Gas	Steam Turbine, Natural Gas	Not Cogen	Los Angeles	1570
St. Luke Medical Center	Natural Gas		Cogen	Los Angeles	1
Techni-Cast Corp.	Natural Gas		Cogen	Los Angeles	1.063
Cbs Studios	Natural Gas		Cogen	Los Angeles	1.4
Ucla Cogen	Natural Gas		Cogen	Los Angeles	43
Redondo Beach Generating Stat	Natural Gas		Not Cogen	Los Angeles	1317
Southern California Gas - Scaqmd	Oil/Gas	Fuel Cell/Wasteheat Recovery	Cogen	Los Angeles	0.2
Wilmington	Waste Heat	Steam Turbine	Not Cogen	Los Angeles	31.9
Total Energy Facility	Digester Gas	Gas Turbine Combined Cycle	Cogen	Los Angeles	25

Puente Hills Recovery	Landfill Gas	Gas Turbine	Not Cogen	Los Angeles	7.8
Palos Verdes Gas To Energy Facility	Landfill Gas	Reciprocating Engine	Not Cogen	Los Angeles	13
Spadra Landfill Gas To Energy	Landfill Gas	Steam Turbine	Not Cogen	Los Angeles	9.9
Mm West Corvina Llc	Msw	Landfill Gas Recovery, Steam Turbine	Not Cogen	Los Angeles	3.25
Southeast Resource Recovery	Msw	Municipal Solid Waste	Not Cogen	Los Angeles	34.6
Penrose	Msw	Reciprocating Engine	Not Cogen	Los Angeles	9.25
Toyon	Msw	Reciprocating Engine	Not Cogen	Los Angeles	9.3
Mm Lopez Energy Llc	Msw	Reciprocating Engine	Not Cogen	Los Angeles	6.6
Commerce Refuse To Energy	Msw	Steam Turbine	Not Cogen	Los Angeles	11.5
San Joaquin Power Co.	Natural Gas		Cogen	Merced	10.75
J.R. Woods Inc.	Msw	Landfill Gas	Cogen	Merced	1.05
Calpine King City Cogen	Natural Gas	Combined Cycle	Cogen	Monterey	130
Sargent Canyon Cogen	Natural Gas	Gas Turbine	Cogen	Monterey	38
Salinas River Cogen	Natural Gas	Gas Turbine	Cogen	Monterey	49.6
Moss Landing	Natural Gas	Steam Turbine	Not Cogen	Monterey	2545
Asilomar	Natural Gas		Cogen	Monterey	0.55
Soledad State Prison	Natural Gas		Cogen	Monterey	2.2
Monterey Power Co.	Natural Gas		Cogen	Monterey	6
Calpine King Energy	Natural Gas	Brown Field	Not	Monterey	50

Center			Cogen		
Monterey Regional Water Pollution Control Cogen	Msw	Digester Gas	Cogen	Monterey	1.74
Salinas	Msw	Internal Combustion	Not Cogen	Monterey	1.4
Marina Landfill Gas	Msw	Landfill Gas	Not Cogen	Monterey	5.4
Napa State Hospital	Natural Gas	Gas Turbine	Cogen	Napa	1.6
Yountville Cogen	Natural Gas	Gas Turbine	Cogen	Napa	3
American Canyon Power Plant	Landfill Gas	Reciprocating Engine	Not Cogen	Napa	1.76
Huntington Beach	Distillate Oil	Steam Turbine, Gas Turbine	Not Cogen	Orange	880
Chiquita Water Reclamation	Methane	Recipocating Engine	Not Cogen	Orange	0.27
Unocal Research	Natural Gas	Combustion Turbine/Topping Cycle	Cogen	Orange	3.623
Southern California Gas - Hyatt Regency	Natural Gas	Fuel Cell/Wasteheat Recovery	Cogen	Orange	0.2
Turbine Tech	Natural Gas	Gas Fueled Reciprocating Engine	Cogen	Orange	0.15
American Mcgaw #2	Natural Gas	Gas-Turbine	Cogen	Orange	6.1
Anaheim Gas Turbine	Natural Gas	Gas Turbine, Natural Gas	Not Cogen	Orange	45.55
Pca Metal Finishing	Natural Gas	Gas-Fueled Reciprocating Engine	Cogen	Orange	0.1
American Cornerstone - Holiday Inn	Natural Gas	Gas-Fueled Reciprocating Engine	Cogen	Orange	0.15
All Metals Processing	Natural Gas	Gas-Fueled Reciprocating Engine	Cogen	Orange	0.175

Royalty Carpet Mills	Natural Gas	Gas-Fueled Reciprocating Engine	Cogen	Orange	0.425
Red Lion Inn	Natural Gas	Gas-Fueled Reciprocating Engine	Cogen	Orange	0.46
Orange County Sanitation District Plant 1	Natural Gas	Gas-Fueled reciprocating Engine	Cogen	Orange	4.5
American Mcgaw	Natural Gas	Steam Turbine & Gas Turbine	Cogen	Orange	8.6
Aliso Water Management Agency	Digester Gas	Digester Gas/Municipal	Not Cogen	Orange	1.2
Plant No. 2	Digester Gas	Digester Gas/Other	Not Cogen	Orange	18
Mm Prima Deschecha Energy Llc	Landfill Gas	Reciprocating Engine	Not Cogen	Orange	6.1
Coyote Canyon	Landfill Gas	Steam Turbine	Not Cogen	Orange	20
Brea Power Partners Lp	Msw	Reciprocating Engine	Not Cogen	Orange	5.4
Kings Beach	Diesel	Internal Combustion	Not Cogen	Placer	16.2
Roseville	Natural Gas	Combustion Turbine	Not Cogen	Placer	53.75
Spi- Lincoln	Woodwaste	Steam Turbine	Cogen	Placer	13
Rio Bravo Rocklin	Woodwaste	Steam Turbine	Not Cogen	Placer	24.4
Coachella	Natural Gas	Combustion Turbine, Natural Gas	Not Cogen	Riverside	80
Municipal Cogen	Natural Gas	Gas Turbine	Cogen	Riverside	1.3
Corona Cogen	Natural Gas	Gas Turbine	Cogen	Riverside	47
Springs Generation Project	Natural Gas	Gas Turbine	Not Cogen	Riverside	40

Eua/Frcii - Monterey Country Club	Natural Gas	Gas-Fueled Reciprocating Engine	Cogen	Riverside	0.115
Eua/Frcii - Palm Valley Country Club	Natural Gas	Gas-Fueled Reciprocating Engine	Cogen	Riverside	0.41
Ces Energy Alberhill	Natural Gas	Gas-Fueled Reciprocating Engine	Cogen	Riverside	0.56
Ces Energy Corona - Pacific Clay	Natural Gas	Gas-Fueled Reciprocating Engine	Cogen	Riverside	0.6
Eua/Frcii - Vintage Country Club	Natural Gas	Gas-Fueled Reciprocating Engine	Cogen	Riverside	0.6
City Of Palm Springs - Sunrise Plaza	Natural Gas	Gas-Fueled Reciprocating Engine	Cogen	Riverside	0.641
Wildflower - Indigo	Natural Gas	Green Field	Not Cogen	Riverside	135
Mecca Plant	Ag. & Woodwaste	Steam Turbine, Cfb	Not Cogen	Riverside	47
Corona Landfill	MSW	Landfill Gas Recovery	Not Cogen	Riverside	0.6
Carson Cogen	Natural Gas	Combustion Turbine With Waste Heat	Cogen	Sacramento	97
Spac	Natural Gas	Combustion Turbine With Waste Heat	Cogen	Sacramento	146
Proctor & Gamble - Smud	Natural Gas	Combustion Turbine With Waste Heat	Cogen	Sacramento	193.4
Mcclellan	Natural Gas	Combustion Turbine, Natural Gas	Not Cogen	Sacramento	49
Kiefer Landfill Gas To Energy Facility	Landfill Gas	Methane Gas		Sacramento	8.3
Century	Natural Gas		Not Cogen	San Bernadino	40
Txi Riverside Cement Power House	Coal	Coal Fired Bottoming Cycle	Cogen	San Bernardino	17
Argus Cogen Plant	Coal	Coal-Fired Topping	Cogen	San Bernardino	55

		Cycle			
Ace Xeration	Coal	Coal-Fired Topping Cycle	Not Cogen	San Bernardino	108
Etiwanda	Distillate Oil	Steam Turbine, Gas Turbine	Not Cogen	San Bernardino	770
High Desert Power Plant Project	Natural Gas	Combined Cycle	Not Cogen	San Bernardino	750
Westend	Natural Gas	Combustion Turbine/Topping Cycle	Cogen	San Bernardino	15
Victor Valley Community Hospital	Natural Gas	Gas Fueled Reciprocating Engine	Cogen	San Bernardino	0.135
Transamerican Plastics	Natural Gas	Gas Fueled Reciprocating Engine	Cogen	San Bernardino	0.34
Indeck Ontario	Natural Gas	Gas Turbine	Cogen	San Bernardino	12
Ontario Mill	Natural Gas	Gas Turbine	Cogen	San Bernardino	34
Loma Linda University	Natural Gas	Gas Turbine, Steam Turbine, Internal Com	Cogen	San Bernardino	13.4
Rialto Usd	Natural Gas	Gas-Fueled Reciprocating Engine	Cogen	San Bernardino	0.1
Rimrock Village Partership	Natural Gas	Gas-Fueled Reciprocating Engine	Cogen	San Bernardino	0.12
Micro Utility - Lake Arrowhead Hilton	Natural Gas	Gas-Fueled Reciprocating Engine	Cogen	San Bernardino	0.28
San Antonio Hospital	Natural Gas	Gas-Fueled Reciprocating Engine	Cogen	San Bernardino	1.8
Mcanally Egg Ranch	Natural Gas	Natural Gas	Cogen	San Bernardino	0.12
Riverside Canal Power	Natural Gas	Steam Turbine	Not Cogen	San Bernardino	160
Mountainview Power Co. - San Bernardino	Natural Gas	Stream Turbine	Not Cogen	San Bernardino	126
Coolwater	Natural Gas	Steam Turbine, Combined Cycle	Not Cogen	San Bernardino	726.3

Chino Nug	Natural Gas, Distill	Combined Cycle/Topping Cycle	Cogen	San Bernardino	27.6
Drews	Natural Gas	Brown Field	Not Cogen	San Bernardino	40
Division	Distillate Oil	Gas Turbine	Not Cogen	San Diego	13
El Cajon	Distillate Oil	Gas Turbine	Not Cogen	San Diego	13
Chula Vista Cogen	Natural Gas	Combined Cycle	Cogen	San Diego	9
Miramar	Natural Gas	Combustion Turbine	Not Cogen	San Diego	33
Ntc Central	Natural Gas	Combustion Turbine With Waste Heat	Cogen	San Diego	16
Naval Station	Natural Gas	Combustion Turbine With Waste Heat	Cogen	San Diego	26
Va Hospital	Natural Gas	Gas Trubine	Cogen	San Diego	0.85
Hotel Del Coronado	Natural Gas	Gas Turbine	Cogen	San Diego	0.8
Palomar Hospital	Natural Gas	Gas Turbine	Cogen	San Diego	1.3
Children's Hospital	Natural Gas	Gas Turbine	Cogen	San Diego	1.5
Grossmont Hospital	Natural Gas	Gas Turbine	Cogen	San Diego	1.6
Medical Center Hospital	Natural Gas	Gas Turbine	Cogen	San Diego	2.4
Qualcomm	Natural Gas	Gas Turbine	Cogen	San Diego	2.4
Sdsu Main	Natural Gas	Gas Turbine	Cogen	San Diego	3
Union-Tribune Publishing Co.	Natural Gas	Gas Turbine	Cogen	San Diego	3
R.J. Donovan Correctional Facility	Natural Gas	Gas Turbine	Cogen	San Diego	3.13
Sea World	Natural Gas	Gas Turbine	Cogen	San Diego	3.5
Nutra Sweet Kelco.	Natural Gas	Gas Turbine	Cogen	San Diego	24
North Island Energy	Natural Gas	Gas Turbine	Cogen	San Diego	38.55

Facility					
Goal Line	Natural Gas	Gas Turbine	Cogen	San Diego	51.4
Solar Turbines Inc.	Natural Gas	Gas Turbine	Not Cogen	San Diego	8.9
North Island	Natural Gas	Gas Turbine	Not Cogen	San Diego	34
Kearny	Natural Gas	Gas Turbine	Not Cogen	San Diego	207
Naval Station/ Navaltraining Center	Natural Gas	Gas Turbine, Steam Turbine	Cogen	San Diego	49.9
Trw	Natural Gas	Gas Turbine/Internal Combustion	Cogen	San Diego	1.3
Bf Goodrich Xeration Plant	Natural Gas	Internal Combustion	Cogen	San Diego	9.495
El Conquistador	Natural Gas	Reciprocating Engine	Cogen	San Diego	0.1
The Wave	Natural Gas	Reciprocating Engine	Cogen	San Diego	0.12
Grossmont Community College	Natural Gas	Reciprocating Engine	Cogen	San Diego	0.2
939 Coast Management	Natural Gas	Reciprocating Engine	Cogen	San Diego	0.23
Alliant Food Service Inc.	Natural Gas	Reciprocating Engine	Cogen	San Diego	0.29
Pomerado Hospital	Natural Gas	Reciprocating Engine	Cogen	San Diego	0.35
Le Meridien Hotel I	Natural Gas	Reciprocating Engine	Cogen	San Diego	0.6
Hunter Industries	Natural Gas	Reciprocating Engine	Cogen	San Diego	0.69
Mercy Hospital Ii	Natural Gas	Reciprocating Engine	Cogen	San Diego	0.8
Mariott Hotel & Marina Ii - South	Natural Gas	Reciprocating Engine	Cogen	San Diego	0.8
Mariott Hotel & Marina I - North	Natural Gas	Reciprocating Engine	Cogen	San Diego	0.8
Southwest Marine	Natural Gas	Reciprocating Engine	Cogen	San Diego	1.3

Salk Institute	Natural Gas	Reciprocating Engine	Cogen	San Diego	1.3
Encina Water Pollution Control	Natural Gas	Reciprocating Engine	Cogen	San Diego	1.425
Ucsd	Natural Gas	Reciprocating Engine	Cogen	San Diego	1.5
San Diego Power & Cooling Co.	Natural Gas	Reciprocating Engine	Cogen	San Diego	1.6
Navy Reg. Data Automation Center	Natural Gas	Reciprocating Engine	Cogen	San Diego	2.6
Kyoceraproject	Natural Gas	Reciprocating Engine	Cogen	San Diego	3.2
South Bay Regional Center	Natural Gas	Steam Turbne	Cogen	San Diego	0.6
South Bay	Natural Gas	Steam Turbine, Gas Turbine	Not Cogen	San Diego	706
Encina	Natural Gas	Steam Turbines & Gas Turbine	Not Cogen	San Diego	971
Csc Western Center Cogen	Natural Gas	Turbine	Cogen	San Diego	3.5
Holiday Inn Embarcadero	Natural Gas		Cogen	San Diego	0.297
Pacific Bell	Natural Gas		Not Cogen	San Diego	6.42
Calpeak Border, Llc Phase I	Natural Gas		Not Cogen	San Diego	49.5
Calpeak Escondido	Natural Gas		Not Cogen	San Diego	49.5
Calpeak Power El Cajon, Llc	Natural Gas			San Diego	48.68
Ntc/Mcrd Energy Facility	Steam & Natural Gas	Combined Cycle	Cogen	San Diego	25.6
Wildflower -Larkspur	Natural Gas	Green Field	Not Cogen	San Diego	90
Gas Utilization Facility	Digester Gas	Internal Combustion	Not Cogen	San Diego	6.8

San Marcos	Landfill Gas	Gas Turbine	Not Cogen	San Diego	1.8
Sycamore San Diego	Landfill Gas	Gas Turbine	Not Cogen	San Diego	1.8
Mm San Diego Llc - Miramar	Landfill Gas	Internal Combustion	Not Cogen	San Diego	6.5
Mm San Diego Llc - North City	Landfill Gas	Landfill Gas	Not Cogen	San Diego	3.8
Otay	Landfill Gas	Reciprocating Engine	Not Cogen	San Diego	3.87
Southeast Digester Gas Cogen	Digester Gas	Internal Combustion	Cogen	San Fracisco	2.1
Hunters Point	Distillate Oil	Gas Combustion Turbine,Steam Turbine	Not Cogen	San Francisco	215
Usf	Natural Gas	Gas Turbine	Cogen	San Francisco	1.5
Potrero	Natural Gas	Gas Turbine	Cogen	San Francisco	362
J.R. Simplot Company	Waste Heat	Steam Turbine, Waste Heat/Sulfuric Acid	Not Cogen	San Joaqiun	4
Port Of Stockton District Energy Facility	Distillate Oil	Steam Turbine	Cogen	San Joaquin	49.9
Stockton Cogen Co.	Natural Gas	Steam Turbine, W/Steam	Cogen	San Joaquin	55.1
Lodi	Natural Gas	Combustion Turbine	Not Cogen	San Joaquin	26.45
Gianera	Natural Gas	Combustion Turbine	Not Cogen	San Joaquin	32.31
Ncpa Stig	Natural Gas	Combustion Turbine	Not Cogen	San Joaquin	49
Corn Products	Natural Gas	Gas Turbine	Cogen	San Joaquin	2.812
Byron Power Co.	Natural Gas	Gas Turbine	Cogen	San Joaquin	6.5
Ripon Mill	Natural Gas	Gas Turbine	Cogen	San Joaquin	49.5
Fisher Nursery	Natural Gas		Cogen	San Joaquin	0.1

Stockton Wwtp	Natural Gas		Cogen	San Joaquin	1.35
San Joaquin Cogen	Natural Gas		Cogen	San Joaquin	49.9
Gwf Tracy Peaker	Natural Gas	Brown Field	Not Cogen	San Joaquin	169
Diamond Walnut	Ag. Waste	Steam Turbine, Grate	Cogen	San Joaquin	4.5
Tracy Biomass Plant	Woodwaste	Steam Turbine, Grate	Not Cogen	San Joaquin	23
Sri International	Natural Gas	Gas Turbine	Cogen	San Mateo	6
United Cogen Inc.	Natural Gas	Gas Turbine, Steam Turbine	Cogen	San Mateo	31
Marsh Road Power Plant	Landfill Gas	Reciprocating Engine	Not Cogen	San Mateo	2
Ellwood	Distillate Oil	Combustion Turbine	Not Cogen	Santa Barbara	54
Santa Ynez	Natural Gas	Combustion Turbine/Topping Cycle	Cogen	Santa Barbara	49.3
Santa Barbara County Jail	Natural Gas	Fuel Cell/Wasteheat Recovery	Cogen	Santa Barbara	0.2
Santa Maria Cogen	Natural Gas	Gas Turbine	Cogen	Santa Barbara	9.5
Gaviota	Natural Gas	Gas Turbine	Cogen	Santa Barbara	14
Santa Barbara Cottage Hospital	Natural Gas		Cogen	Santa Barbara	6.4
O'brien Energy Systems - Santa Maria	Natural Gas		Cogen	Santa Barbara	43
Southern California Gas - Ucsb	Oil/Gas	Fuel Cell/Wasteheat Recovery	Cogen	Santa Barbara	0.2
Mm Tajiguas Energy Llc	Landfill Gas	Reciprocating Engine	Not Cogen	Santa Barbara	3.1
Gilroy Cogen	Natural Gas	Combined Cycle	Cogen	Santa Clara	123.4
City Of Santa Clara	Natural Gas	Combustion Turbine With Waste Heat	Cogen	Santa Clara	5.8

San Jose Convention Center	Natural Gas	Gas Turbine	Cogen	Santa Clara	1.5
San Jose Cogen	Natural Gas	Gas Turbine	Cogen	Santa Clara	6
Cardinal Cogen	Natural Gas	Gas Turbine, Steam Tubine	Cogen	Santa Clara	52.9
Jefferson Smurfit	Natural Gas	Gas Turbine, Steam Turbine	Cogen	Santa Clara	26.8
Los Esteros Energy Center	Natural Gas	Steam Turbine	Not Cogen	Santa Clara	180
Agnews	Natural Gas		Cogen	Santa Clara	36.1
Gilroy Energy Center	Natural Gas	Brown Field	Not Cogen	Santa Clara	135
Santa Clara	Landfill Gas	Internal Combustion	Not Cogen	Santa Clara	1.5
Newby Island 2	Landfill Gas	Recipocating Engine	Not Cogen	Santa Clara	3.3
Newby Land 1	Landfill Gas	Reciprocating Engine	Not Cogen	Santa Clara	2
Byxbee Park Sanitary Landfill	Landfill Gas	Reciprocating Engine	Not Cogen	Santa Clara	2
Guadalupe Power Plant	Landfill Gas	Reciprocating Engine	Not Cogen	Santa Clara	2.6
Watsonville Cogen	Natural Gas	Steam Turbine, Gas Turbine	Cogen	Santa Cruz	31
Water Street Jail	Natural Gas		Cogen	Santa Cruz	0.18
Uc Santa Cruz Sports Facility	Natural Gas		Cogen	Santa Cruz	0.29
Owl Companies	Natural Gas		Cogen	Santa Cruz	0.6
Santa Cruz Wwtp	Natural Gas		Cogen	Santa Cruz	0.65
Santa Cruz Cogen	Natural Gas		Cogen	Santa Cruz	2.635
Solano Cogen	Natural Gas	Gas Turbine	Cogen	Solano	1.45
Lambie Energy	Natural Gas	Gas Turbine		Solano	48.1

Center					
Wolfskill Energy Center	Natural Gas	Gas Turbine		Solano	48.1
Creed Energy Center	Natural Gas	Gas Turbine		Solano	48.1
Goose Haven Energy Center	Natural Gas	Gas Turbine		Solano	48.1
City Of Vacaville - Community Center	Natural Gas		Cogen	Solano	0.45
City Of Fairfield	Natural Gas		Cogen	Solano	0.775
California Medical Facility	Natural Gas		Cogen	Solano	1.5
Calpeak Power Vaca Dixon, Llc	Natural Gas			Solano	49.95
Valero Unit 1 & 2	Natural Gas	Combustion Turbine, Brown Field	Not Cogen	Solano	47.7
Laguna Plant Co-Gen Facility	Natural Gas	Internal Combustion	Not Cogen	Sonoma	2.7
Central Lf (Sonoma) Phase I	Landfill Gas	Internal Combustion Engine	Not Cogen	Sonoma	3.2
Central Lf (Sonoma) Phase Ii	Landfill Gas	Internal Combustion Engine	Not Cogen	Sonoma	3.2
Mcclure	Distillate Oil	Combustion Turbine	Not Cogen	Stanislaus	117
Almond	Natural Gas	Combined Cycle	Not Cogen	Stanislaus	49.5
Woodland I & Ii	Natural Gas	Combustion Turbine With Waste Heat, Cc	Cogen	Stanislaus	129.4
Walnut	Natural Gas	Gas-Fueled Turbine	Not Cogen	Stanislaus	48.5
Hershey Chocolate	Natural Gas	Internal Combustion	Cogen	Stanislaus	6.2
Modesto Energy	Msw	Steam Turbine	Not Cogen	Stanislaus	14

Stanislaus Resource Recovery Facility	Msw	Steam Turbine	Not Cogen	Stanislaus	22.5
Sutter Power Project	Natural Gas	Xeration, Steam To Uss-Posco	Not Cogen	Sutter	540
Yuba City Energy Center	Natural Gas	Gas Turbine	Cogen	Sutter	48.1
Yuba City Cogen	Natural Gas	Gas Turbine	Cogen	Sutter	49
Greenleaf Unit Two	Natural Gas	Gas Turbine	Cogen	Sutter	49.5
Feather River Energy Center	Natural Gas	Gas Turbine		Sutter	48.1
Greenleaf Unit One	Natural Gas	Gas Turbine, Steam Tubine	Cogen	Sutter	61.4
Yuba City Wwtp	Natural Gas		Cogen	Sutter	0.14
Mandalay	Distillate Oil	Steam Turbine, Gas Turbine	Not Cogen	Ventura	560
Camarillo Nug	Natural Gas	Combined Cycle/Topping Cycle	Cogen	Ventura	28.04
Sithe Energies	Natural Gas	Combined Cycle/Topping Cycle	Cogen	Ventura	48.5
Us Government, Naval Engineering Command	Natural Gas	Combustion Turbine/Topping Cycle	Cogen	Ventura	0.8
Vintage Petroleum	Natural Gas	Combustion Turbine/Topping Cycle	Cogen	Ventura	3.3
Oxnard I	Natural Gas	Gas Turbine	Cogen	Ventura	19.295
Hueneme Paper Mill	Natural Gas	Gas Turbine	Cogen	Ventura	25
Oxnard Ii	Natural Gas	Gas Turbine	Cogen	Ventura	49.5
Oxnard Wwtp	Natural Gas	Gas Turbine Combined Cycle	Cogen	Ventura	1.5
Oxnard Hs	Natural Gas	Gas-Fueled Reciprocating Engine	Cogen	Ventura	0.12

Doubletree Hotel	Natural Gas	Gas-Fueled Reciprocating Engine	Cogen	Ventura	0.2
City Of Ventura - Eastside Wtr Renovation	Natural Gas	Gas-Fueled Reciprocating Engine	Cogen	Ventura	0.548
Rockwell Intl. - Kalina	Natural Gas	Miscellaneous/Bottoming Cycle	Cogen	Ventura	3.5
Rockwell Intl.	Natural Gas	Miscellaneous/Bottoming Cycle	Cogen	Ventura	28
Ormond Beach	Natural Gas	Steam Turbine	Not Cogen	Ventura	1492
Unocal Rincon Cogen	Natural Gas	Steam Turbine/Enhanced Oil Recovery	Cogen	Ventura	3.5
Oxnard	Landfill Gas	Internal Combustion	Not Cogen	Ventura	5.55
UC Davis	Natural Gas	Gas Turbine	Cogen	Yolo	3
Woodland Biomass Power Ltd	Ag. & Woodwaste	Steam Turbine	Not Cogen	Yolo	28
Mm Yolo Power LLC Facility	Landfill Gas	Reciprocating Engine	Not Cogen	Yolo	2.85

b) Rural power plants

PLANTNAME	PRIMARY FUEL	TECHNOLOGY	COGEN	COUNTY	ONLINE MW
Jackson Valley Energy Lp	Lignite Coal	Steam Turbine	Cogen	Amador	17.99
Mule Creek State Prison	Natural Gas	Internal Combustion	Cogen	Amador	3
Wheelabrator Martell Inc.	Woodwaste	Steam Turbine	Cogen	Amador	18
Wadham	Rice By Products	Steam Turbine	Not Cogen	Colusa	29.5
Csu Humboldt	Natural Gas	0	Cogen	Humboldt	0.35
Samoa Pacific Cellulose, Llc	Natural Gas	Steam Turbine	Cogen	Humboldt	20
Pacific Lumber Co.	Woodwaste	Steam Turbine	Cogen	Humboldt	32.5
Ultrapower 3 Blue Lake	Woodwaste	Steam Turbine	Not Cogen	Humboldt	13.806
Farihaven Power Co.	Woodwaste	Steam Turbine	Not Cogen	Humboldt	15
Brawley	Distillate Oil	Combustion Turbine	Not Cogen	Imperial	20
Rockwood	Natural Gas	Combustion Turbine	Not Cogen	Imperial	46
El Centro	Natural Gas	Steam Turbine, Combined Cycle	Not Cogen	Imperial	80
Mesquite Resource Recovery Project	Ag. & Animal Waste	Steam Turbine, Grate	Not Cogen	Imperial	17.89
Rio Bravo Poso	Coal	Steam Turbine	Cogen	Kern	33
Rio Bravo Jasmin	Petroleum Coke	Steam Turbine	Cogen	Kern	33
Mt. Poso Cogeneration	Natural Gas/Eor	Steam Turbine	Cogen	Kern	63.64

La Paloma Generating Project	Natural Gas	Combined Cycle	Not Cogen	Kern	968
Sunrise Power Project	Natural Gas	Fired Cogeneration (For Teor)	Cogen	Kern	320
Arco - Fee "B"	Natural Gas	Gas Turbine	Cogen	Kern	3.725
Welport Project	Natural Gas	Gas Turbine	Cogen	Kern	3.8
Frito-Lay	Natural Gas	Gas Turbine	Cogen	Kern	6
Dome Project	Natural Gas	Gas Turbine	Cogen	Kern	6.6
Arco - Fee "C"	Natural Gas	Gas Turbine	Cogen	Kern	7.45
Arco - Fee "A"	Natural Gas	Gas Turbine	Cogen	Kern	7.925
Texaco - Mckittrick	Natural Gas	Gas Turbine	Cogen	Kern	10.969
North Midway	Natural Gas	Gas Turbine	Cogen	Kern	10.97
Chevron - Taft	Natural Gas	Gas Turbine	Cogen	Kern	12.5
Chevron Cymric	Natural Gas	Gas Turbine	Cogen	Kern	26.3
Dai/Oildale Cogen	Natural Gas	Gas Turbine	Cogen	Kern	31
Berry Cogen - Midway Sunset	Natural Gas	Gas Turbine	Cogen	Kern	38.7
Midset Cogen	Natural Gas	Gas Turbine	Cogen	Kern	39
Oildale Cogen	Natural Gas	Gas Turbine	Cogen	Kern	40
Boron	Natural Gas	Gas Turbine	Cogen	Kern	45
Chalk Cliff Cogen	Natural Gas	Gas Turbine	Cogen	Kern	47
Badger Creek Ltd.	Natural Gas	Gas Turbine	Cogen	Kern	47
South Belridge Cogen	Natural Gas	Gas Turbine	Cogen	Kern	48
Double "C" Ltd.	Natural Gas	Gas Turbine	Cogen	Kern	53.6
High Sierra Ltd.	Natural Gas	Gas Turbine	Cogen	Kern	53.6
Kern Front Ltd.	Natural Gas	Gas Turbine	Cogen	Kern	53.6
Bear Mountain Ltd.	Natural Gas	Gas Turbine	Cogen	Kern	68.82
Live Oak Cogen	Natural Gas	Gas Turbine	Cogen	Kern	68.82

Mckittrick Cogen	Natural Gas	Gas Turbine	Cogen	Kern	72
Kern River Cogen	Natural Gas	Gas Turbine	Cogen	Kern	300
Sycamore Cogen	Natural Gas	Gas Turbne	Cogen	Kern	300
Elk Hills	Natural Gas	Gas Turbine	Not Cogen	Kern	500
Mohave Cogen	Natural Gas	Gas Turbine, Stesm Turbine	Cogen	Kern	56.4
M.H. Whittier Cal	Natural Gas	0	Cogen	Kern	0.5
Cal Resources - N. Midway Sunset	Natural Gas	0	Cogen	Kern	4.25
Arco Oxford	Natural Gas	0	Cogen	Kern	5.2
Occidental Of Elk Hills Inc.	Natural Gas	0	Cogen	Kern	10
Lost Hills	Natural Gas	0	Cogen	Kern	10.969
Berry Petroleum Co.	Natural Gas	0	Cogen	Kern	17
Midsun Partners	Natural Gas	0	Cogen	Kern	27.35
Sekr Cogen	Natural Gas	0	Cogen	Kern	34.468
Chevron - Kern River Eastridge	Natural Gas	0	Cogen	Kern	44
Sunrise Ii Combined Cycle Expansion	Natural Gas	0	Not Cogen	Kern	265
Midway-Sunset Cogen	Natural Gas/Eor	Gas Turbine	Cogen	Kern	242
Delano Energy Co. Inc.	Ag. & Woodwaste	Agricultural Waste	Not Cogen	Kern	56.5
Spi- Susanville	Woodwaste	Steam Turbine	Cogen	Lassen	14.34
Mt. Lassen Power	Woodwaste	Steam Turbne	Cogen	Lassen	11.4
Big Valley Lumber Co.	Woodwaste	Steam Turbine, W/Steam	Cogen	Lassen	7.5
Hi Power Co.	Woodwaste	0	Cogen	Lassen	35.5
Heublein Wines	Natural Gas	0	Cogen	Madera	0.325

Fort Bragg Western Wood Products	Woodwaste	0	Not Cogen	Mendocino	15
Portola	Diesel	Internal Combustion	Not Cogen	Plumas	5.7
Collins Pine Co. Project	Woodwaste	Steam Turbine	Cogen	Plumas	12
Spi- Quincy	Woodwaste	Steam Turbine	Cogen	Plumas	27.5
Morro Bay	Natural Gas	Steam Turbine	Not Cogen	San Luis Obispo	1021
Koch California Ltd.	Natural Gas	0	Cogen	San Luis Obispo	0.3
Lassen Energy	Natural Gas	Gas Turbine	Cogen	Shasta	38.8
Redding Power	Natural Gas	Steam Turbine & Combustion Turbines	Not Cogen	Shasta	97.2
City Of Redding	Natural Gas	0	Cogen	Shasta	28
Spi- Anderson	Woodwaste	Fuel Cell Gasification	Cogen	Shasta	4
Wheelabator Hudson Energy	Woodwaste	Steam Turbine	Cogen	Shasta	6.8
Burney Mountain Power	Woodwaste	Steam Turbine	Cogen	Shasta	11.4
Spi- Burney	Woodwaste	Steam Turbine	Cogen	Shasta	20
Burney Forest Products	Woodwaste	Steam Turbine	Cogen	Shasta	31
Wheelabrator Shasta	Woodwaste	Steam Turbine	Cogen	Shasta	62.75
Downieville	Diesel	Combustion Turbine	Not Cogen	Sierra	0.7
Spi- Loyalton	Woodwaste	Steam Turbine	Cogen	Sierra	20
Tulare Detention Facility	Natural Gas	Gas Fueled Reciprocating Engine	Cogen	Tulare	0.55
Kaweah Hospital	Natural Gas	Gas Turbine	Cogen	Tulare	1
Mm Tulare Energy Llc	Landfill Gas	Gas Turbine Combined Cycle	Not Cogen	Tulare	1.8

Pacific Ultrapower Chinese Station	Woodwaste	Steam Turbine	Not Cogen	Tuolumne	25
Spi- Sonora	Woodwaste	Traveling Grate	Cogen	Tuolumne	7.5